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# LOW ENERGY ELECTRONS IN THE MAGNETOSPHERE

BY  
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**LOW-ENERGY ELECTRONS  
AND THE  
MAGNETOSPHERE**

by  
**Peter Serlemitsos**

Thesis submitted to the Faculty of the Graduate School  
of the University of Maryland in partial fulfillment  
of the requirements for the degree of  
Doctor of Philosophy  
1965

## ABSTRACT

Title of thesis: Low-Energy Electrons and the Magnetosphere

Peter Serlemitsos, Doctor of Philosophy, 1965

Thesis directed by: Frank B. McDonald  
Visiting Professor

11230  
We are presenting in this work a number of observations on satellite data which pertain to low-energy ( $\sim 100$  keV) electrons in the earth's magnetosphere, and which were obtained with detectors aboard the scientific satellites Explorers XII and XIV. These data cover essentially all low-latitude regions in the magnetosphere, between about 4.5 and 16 Re..

In connection with the sunward side, we have investigated the temporal and spatial characteristics of the observed outer boundary of the trapping region, and have compared our observations with other relevant information and with theoretical considerations.

With regard to the dark side of the magnetosphere, we have presented information concerning the extent and the nature of the trapping region there, the pitch-angle distributions of trapped electrons and the general picture of the distant trapping field, as deduced from the anisotropic features of these electrons. In addition, we have studied the electron fluxes which appear outside the trapping region, with regard to certain temporal and spatial features, such as anisotropies, radial dependence and dependence on magnetic latitude. Possible correlations between these fluxes and ground magnetograms, riometer records, and other satellite data have been considered.

The results of this investigation are discussed, with emphasis on the new findings and their possible interpretations.

*Author*

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The reduction and analysis of these data necessitated the combined efforts of many persons, of which I would like to make special mention of Miss G. Cigarski, Mrs. G. Pearson, and Messrs. R. Fisk, L. Hyatt, C. Clemens, G. Shearer, H. Caulk, and A. Thomson.

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## I. INTRODUCTION

It is well known that many geophysical phenomena are made possible only through extraterrestrial influences which are primarily of solar origin. A group of such phenomena are, for example, those associated with time variations in the earth's magnetic field. Of particular importance is an identifiable pattern of large magnetic field variations, containing both world-wide and local components and comprising what is known as a magnetic storm. These field variations, as well as accompanying phenomena such as aurorae, involve the expenditure of large amounts of energy whose origin has long been suspected to be the sun. Attempts to explain how this energy reaches the earth have been made even before the turn of this century and were primarily based either upon an assumed solar corpuscular emission or upon solar ultraviolet radiation. Lindemann [1919] suggested that the solar influence in this case may be propagated by a neutral but ionized solar stream which would travel away from the sun with a velocity of about 800 km/sec and reach the earth without appreciable recombination.

Chapman and Ferraro [1931, 1932, 1933, 1940] considered in detail the theoretical aspects of the interaction resulting from the sudden arrival of such a stream in the vicinity of the earth. In their model, they assumed the absence of any collective behavior among the charged particles in the stream, so that these particles will undergo specular reflection upon reaching the geomagnetic field, ions curving one way, the electrons curving oppositely. An electric current will result whose effect would be to reduce the magnetic field producing

it inside the stream's surface, while increasing the field strength in front of this surface. Thus, if the solar plasma is originally field-free, it will remain so during the progress of its interaction with the geomagnetic field. This interaction compresses in effect the field, until the motion of the stream normal to the resulting interface is stopped, when the pressure of the streaming ions on one side is equal to the magnetic field pressure on the other. It is evident that the gas near the subsolar point will be appreciably retarded whereas, the streaming velocity away from this point will be hardly affected. This means that a cavity will be formed around the earth's sunward side which will completely contain the terrestrial field in that region and whose boundary in relation to the earth's center will be given by the following pressure balance relation.

$$2nmv^2 \cos^2 \theta = B^2/8\pi$$

where  $n$  is the ion density,  $m$  the ion mass,  $v$  the streaming velocity,  $\theta$  the angle between the streaming direction and the outward normal to the boundary and  $B$  is the total magnetic field strength just inside the boundary. This equation is valid only for a stream of ions incident normally onto the earth's dipole. In the aforementioned works, the cavity appears as a temporary rather than a permanent phenomenon; its transient existence coincides with the sudden commencement and the initial phase of a magnetic storm. The possibility of a steady-state situation resulting from a continuing solar stream had not been ruled out however.

In the following years, various investigations produced evidence supporting the existence of a continuously streaming solar gas, which would very likely be intensified during increased solar activity.

Such was the case for example with Biermann's observations on the behavior of comet tails [1957], as well as with other observations on the solar corona, on the scattering of polarized sunlight, etc. Subsequently, a number of works began to emerge in connection with the interaction of this ionized gas or plasma with the geomagnetic field [i.e. Parker, 1958; Dungey, 1958; Gold, 1959; Johnson, 1960; Beard, 1960], particularly since it became apparent that the rather simple Chapman-Ferraro picture left many questions unanswered. Ways were being sought for bringing inside the geomagnetic cavity the large amounts of energy which are required to account for certain geophysical phenomena; questions were raised in connection with the shape and stability of the walls of this cavity, at all angles to the earth-sun line. About this time some new terms appeared in the literature, some of which have been used frequently in later works. The word "magnetosphere" was introduced by Gold [1959] to describe the region of space which is identified with the extent of geomagnetic influence over charged particles. The boundary of the magnetosphere is frequently referred to as the "magnetopause". Finally, Parker [1958] appropriately proposed the name "solar wind" for the streaming solar gas.

The advent of scientific earth satellites and deep space probes made possible important contributions in this field, based on direct experimental evidence. A major discovery occurred when intense fluxes of energetic particles trapped in the geomagnetic field were encountered [Van Allen et al., 1958]. The concept of such particle trapping emerged originally from an investigation by Störmer on the motion of charged

particles near a magnetic dipole. The earth's field may be approximated by such a dipole, at least up to the point where solar-wind induced distortions appear to dominate the distant field. Störmer's work implied that there are certain regions around the earth which are completely inaccessible to charged particles coming from infinity. However, the equations of motion did not exclude the possibility of trapped particles already existing in these regions. Such particles could be confined there for relatively long periods of time while their kinetic energy remained unchanged. The above experimental findings showed that the inaccessible Störmer regions around the earth are indeed filled with charged particles.

Subsequent data from space vehicles confirmed the existence of the solar wind [Gringauz et al., 1960; Bonetti et al., 1963]. It was further established that this solar plasma contains a weak interplanetary magnetic field [Coleman et al., 1960; Heppner et al., 1963]. Data pertaining to the existence of the magnetospheric boundary were also obtained at this time. Before discussing them, we will subdivide the magnetosphere into two regions as suggested by the anisotropic nature of the solar wind. We will refer to them as the sunlit and the dark magnetospheres and all our discussions will be qualified accordingly. The first systematic experimental study of the magnetosphere was accomplished with particle and magnetometer data from the Explorer XII satellite. These data were obtained from the sunlit portion and generally from regions in space near the geomagnetic equatorial plane. They showed a well-defined boundary located at a geocentric distance of about 10 to 11  $R_E$  (earth radii) near the subsolar point

and separating ordered fields and trapped particles from regions of generally small and disordered magnetic fields, often containing large fluxes of superthermal electrons [Cahill and Amazeen, 1963; Freeman et al., 1963]. Evidence of compression of the earth's field due to the impinging solar plasma was seen. Drastic changes in the trapped particle population were correlated with disturbed conditions. To a large extent, some of these findings are consistent with the conclusions contained in the works of Chapman and Ferraro, if we neglect the transient nature of their cavity.

The data from the dark magnetosphere were considerably more complicated. Heppner et al. [1963] found that magnetometer data from the only orbit of Explorer X contained evidence of relatively strong magnetic fields in this region, slowly varying with geocentric distance and extending out to distances in excess of 40 Re, generally directed away from the sun and the earth. Later data from Explorer XIV [Cahill, 1964] were in agreement with this tail-like field configuration which seemed to indicate that tangential stresses may be stretching the field lines out to large distances where they may become connected to the interplanetary field. The region of the magnetosphere which is characterized by such a configuration has been often referred to as the "magnetospheric tail". Energetic particle data from the same satellite showed that highly variable fluxes of 40-keV electrons frequent this region of space, out to a radial extent which appeared to exceed the satellite apogee of about 16 Re [Frank, 1964]. Unlike similar measurements in the sunlit magnetosphere, the particle boundary in the magnetospheric tail seemed for the most part to be poorly defined.

Frank however, found a core of higher electron fluxes, extending out to about 8 Re near the midnight meridian, which could be interpreted as indicating the extent of durably trapped particles.

Second generation satellite experiments have added a great deal more to the foregoing observations. Through the use of more sophisticated detectors, more suitable orbits and improved telemetry, much detailed information in connection with the solar wind, the magnetosphere and the interaction region between the two has been obtained. Thus, a sun-directed plasma probe aboard the Venus-bound vehicle Mariner II detected an always-present solar plasma flow whose positive component consisted mostly of protons, having streaming velocities consistently above 300 km/sec; the higher velocity periods appeared to coincide with enhanced geomagnetic activity. Ionic temperatures were found mostly between  $6 \times 10^4$  and  $5 \times 10^5$  °K (thus indicating a warm plasma), number densities between .3 and 10 protons/cm<sup>3</sup>, energy densities between  $2 \times 10^{-7}$  and  $2 \times 10^{-8}$  ergs/cm<sup>3</sup> [Neugebauer and Snyder, 1962; Snyder and Neugebauer, 1963]. More recently, data from plasma probes aboard the IMP-1 satellite confirmed the anisotropic nature of the solar wind and found the direction of incidence to be that of the earth-sun line [Bridge et al., 1964, 1965]. Magnetometer data from this satellite [Ness et al., 1964] showed a rather steady interplanetary magnetic field between 4 and 7 gammas (1 gamma equals  $10^{-5}$  gauss). With regard to the magnetosphere, IMP-1 data were in agreement with previous particle and field observations. New measurements in the dark side were of particular importance due to the high apogee of this satellite (approximately 31.5 earth radii). There, magnetic data were again

indicative of an open and very extended magnetospheric tail. They also provided evidence on the existence of a neutral sheet separating fields with a generally antisolar direction from those directed toward the sun [Ness, 1965]. Anderson et al. [1965] found that patches of energetic electrons, similar to those detected by Explorer XIV, extended out to the very edge of the satellite apogee. In addition, the IMP-1 data provided experimental evidence supporting a continuum approach to the solar wind-geomagnetic field interaction, as contrasted with the originally adopted idea of individual particle reflections at the edge of the magnetosphere. Such an approach had been proposed before on the basis of some experimental justification derived from earlier data. Before we further discuss these data and particularly those aspects which indicate collective behavior among the solar wind particles, we will review briefly some widely accepted ideas regarding the origin of the solar plasma, as well as some of the physical principles which are expected to govern its behavior.

The solar wind is thought to be a continuous expansion of the solar corona into interplanetary space, which, due to the high conductivity of coronal gases, causes at the same time the extension of the solar magnetic fields by its outward motion [Parker, 1963]. Near the sun, the ion density and temperature are sufficiently high for Coulomb scattering to reduce the mean-free path of the thermal ions below the relevant lengths, such as the scale length and the radial distance. Thus, coronal gases in this region are characterized by fluid behavior and their kinetic properties can be treated using the classical hydrodynamic equations. At this stage, the expansion of these gases is

thought to be near-isothermal. However, as coronal heating and thermal conduction disappear at large distances from the sun, this expansion eventually becomes adiabatic; the temperature and density drop as the gases further expand. Parker has shown that these conditions will result in a monotonic kinetic energy increase so that the expansion velocity will become supersonic beyond a radial distance of a few solar radii from the sun. By the time that the intensified solar wind reaches the earth's orbit, Coulomb collisions between particles have, for all practical purposes, become negligible. However, we cannot discount the possibility of collective behavior among the ions in the stream, since mechanisms involving electric and magnetic fields are known to exist, which can couple the motions of the individual charged particles in a plasma, thus causing effects similar to those which appear when collisions are more frequent.

We may expect widely different magnetospheric effects depending on whether the solar wind interacts with the geomagnetic field as a group of independent charged particles or as a fluid. If the latter description is the correct one, the flow of the solar plasma around the magnetosphere will again be different in character, depending on whether the local solar wind speed is subsonic or supersonic with respect to the propagation velocity of the various waves in the plasma. Of all the relevant propagation modes, Alfvén and magnetoacoustic waves are usually considered to be most important in this case, although other modes could well be of significance [Scarf et al., 1965]. A supersonic flow will cause the formation of a standing shock wave a short distance upstream from the stagnation point, as pointed by

Axford [1962] and Kellogg [1962] among others. In the absence of binary collisions, the necessary entropy increase which must accompany a true shock transition can probably be accounted by a number of plasma instabilities whose growth appears to be easily induced [Parker, 1963].

The existence of the Chapman-Ferraro cavity is not a matter of the particular viewpoint we adopt to describe the solar wind behavior. The shape of this cavity in the sunlit side is very insensitive to the details of the flow. Conditions outside the cavity however, are definitely dependent on such details. The region between the shock front and the magnetospheric boundary is expected to be characteristic of a hot plasma and turbulent magnetic fields [Axford, 1962; Levy et al., 1963]. It is not clear what we can expect at the magnetospheric tail except that it is reasonable to expect considerable convection of hot plasma and turbulence in this region from the sunlit side. Tangential stresses probably have a major role in shaping the magnetic fields here [Axford and Hines, 1961; Axford et al., 1964]. Shock formation can also be expected in interplanetary space, whenever supersonic velocity differences arise, such as when a sudden increase in coronal temperature results in an outburst of fast plasma (i.e. solar flare phenomenon) overtaking the expanse of slower plasma. The resulting disturbance front may cause, as it sweeps past the earth, the sudden commencement of a magnetic storm.

Now turning once more to satellite data we find that the first indication that the region of space just beyond the sunlit magnetopause often contains turbulence and thermalized plasma was obtained

with Explorer XII [Freeman et al., 1963; Freeman, 1963]. A more complete and convincing picture was obtained by the magnetic field and plasma detectors aboard IMP-1 whose measurements indicated conditions very similar to those we would expect if we were to assume the existence of a standing shock beyond the magnetosphere. Repeated crossings of this bow shock indicated that its average location was generally in agreement with calculations based on the analogy of a supersonic gas flow around a blunt body [Ness et al., 1964]. Thus, from these data, it appears that the continuum approach is the correct one when considering solar wind effects on a scale of the order of the earth's magnetosphere. As an afterthought, we may mention that it would be difficult to find a mechanism by which an independent particle flow could transfer adequate amounts of energy from the solar wind into the magnetosphere to account for geomagnetic phenomena. Many such phenomena have been directly linked with a downflux of energetic electrons into the earth's atmosphere [O'Brien, 1962, 1964]. Solar wind measurements have shown that the latter does not contain sufficient numbers of particles with the appropriate energy to directly account for this downflux. On the other hand, trapped particle regions around the earth could sustain the observed electron precipitation for a short time only, if they were not replenished by a source of such particles. If particle acceleration is to take place near the magnetosphere, it may be necessary to have conditions which involve plasma instabilities, shock formation, and other phenomena which can only result from a coherent solar wind.

Charged particles in general are very intimately tied in with magnetospheric processes. As mentioned earlier, a sizeable portion

of the magnetosphere is occupied by trapped radiation, the latter appearing in two distinct zones about the earth. The inner zone consists mostly of high-energy protons (up to several hundred meV) with peak fluxes centered at about 1.5 Re from the earth's center, near the magnetic equatorial plane. The observed proton fluxes in this region are generally stable, (i.e. solar influences are very small) so that these particles have seemingly no connection with geophysical phenomena, which are known to undergo large enhancements during disturbed conditions. The outer radiation zone consists of low-energy electrons and protons (energies up to a few meV) whose peak intensities occur near 4 Re. The soft components of the outer zone fluxes extend to the magnetospheric boundary and are therefore subject to strong solar wind influence. Electrons near the outer edges of the trapping region are similar to those which are precipitating into the atmosphere [O'Brien, 1964]. In fact, both these components appear to undergo similar changes at a given time, thus indicating that they are the direct products of an acceleration process which takes place either inside or outside the magnetosphere. The existence of an acceleration mechanism is also indicated by the large electron fluxes encountered in the magnetospheric tail. These particles cannot be considered trapped for any length of time, in a region of space which has been shown to be characterized by a radial field topology. Tail electrons must therefore be a highly transient phenomenon, just as their appearance in pulse-like clusters would indicate. McDiarmid and Burrows [1965a, 1965b] have suggested that these electrons are produced in the magnetospheric tail itself and that some of them

find their way into the outer radiation zone to replenish the electronic component there. These considerations are certainly in agreement with the suggestion of Axford et al., [1964] that the magnetospheric tail may provide a mechanism for energy input into the body of the magnetosphere. We believe that more detailed information on these electrons, and on electrons generally throughout the magnetosphere and the transition region, will be instrumental in increasing our understanding of magnetospheric processes. Electron data in this region depend on many variables, among which are the time, geocentric distance, magnetic latitude, satellite position relative to the earth-sun line, energy threshold of the detector etc. Thus, it is very unlikely that information obtained from any one satellite will in itself be sufficient to provide unique answers to questions which usually arise in connection with processes in this region. Data interpretation at the present has been made somewhat easier however, by everything that has already been learned.

With the purpose of adding to existing information, we will now present a number of observations based on the magnetospheric electron data from detectors aboard Explorers XII and XIV. These detectors had estimated energy thresholds for magnetospheric electrons around 80 to 100 keV. They were further characterized by a high sensitivity and by good time and spatial resolutions. The specific objectives of this investigation are as follows:

- 1) We will show that trapped electrons in low-latitude portions of the magnetosphere are confined in a region which has a rather distinct and stable boundary throughout the sunlit hemisphere, closely identified with the magnetopause near the magnetic equatorial plane.

We will present evidence to the effect that this region is symmetric about the earth-sun direction but that it displays a strong noon-midnight asymmetry. We will show that its extent as well as the morphology of trapped electrons near its outer boundary show a dependence on geomagnetic activity which becomes very pronounced near the antisolar direction.

2) With regard to the dark magnetosphere we will see that our data indicate that trapped electrons there have a pitch-angle distribution whose maximum undergoes a 90 deg. change through a region of near-isotropic electron fluxes. These data also indicate that the earth's magnetic field in this region is highly distorted having an almost radial appearance at the outermost points of trapping. Evidence of electron streaming along field lines and inside the trapping region will be shown.

3) We will show that electron fluxes outside the trapping region and specifically in the tail of the magnetosphere show a positive correlation with geomagnetic activity, that they are essentially isotropic, and that they are usually seen in pulse-like events whose fast onset correlates with the initiation of magnetic bays seen at auroral stations. We will see that these events are clustered around the geomagnetic equatorial plane and that their frequency decreases with geocentric distance.

4) Our findings will be discussed with emphasis on new contributions to this field.

## II. THE EXPERIMENT

The bulk of magnetospheric studies have thus far been conducted with data from satellites in highly eccentric orbits because such vehicles, in addition to accomplishing several other scientific objectives, have also probed for experimenters at one time or another, large portions of the magnetosphere and of the region just beyond. This can be seen from the following considerations. The satellite motion during one complete orbit is such as to make possible measurements over a large range of geocentric distances. At the same time, due to the earth's motion about the sun, the orientation of the major axis of the satellite orbit changes in relation to the earth-sun direction, so that new variables, upon which magnetosphere measurements depend, enter the picture. The data which we will present in this investigation have been obtained with detectors aboard two scientific satellites whose orbits fit the above description.

Explorer XII was launched on August 16, 1961, into a highly elliptical orbit having an apogee of 83,600 km (geocentric distance), an initial perigee of 6,700 km, a period of 26.5 hours and an inclination of 33 deg. The spatial region of interest covered by this satellite, during its useful lifetime, is shown in Fig. 1. More specifically, this figure shows the projection of this region on the geomagnetic equatorial plane. Other orbital data can be found in a number of publications [i.e. Freeman, 1963]. The greatest portion of our data has come from Explorer XIV which attained a more suitable orbit for our purposes and whose lifetime was considerably longer than that of its predecessor. It was launched on October 2, 1962, into an orbit which was similar in many ways with

the orbit of Explorer XII. An important difference was its higher apogee of 104,800 km, and longer period of 36.4 hours. This satellite transmitted useful information until August 8, 1963, thus covering the area of the geomagnetic equatorial plane shown in Fig. 1. Additional orbital data can be obtained from Frank et al., [1963].

The same cosmic-ray experiment was flown aboard both these satellites. The arrangement of the detectors in the satellite is shown in Fig. 2. A scintillation counter telescope was designed to detect protons of medium ( $> 100$  meV) and high ( $> 1$  beV) energies. A Geiger counter telescope, with a 70 meV proton threshold for coincidence counts, was included to provide additional medium energy measurements. Both the telescope counting rate as well as the counting rate of the top counter were sampled. Our main interest is centered, however, on the third detector shown, a thin CsI (Tl) crystal, 1.9 cm in diameter and  $.5 \text{ gm/cm}^2$  thick, covered with a  $6.5 \text{ mg/cm}^2$  aluminum foil. This detector was designed primarily for the study of low-energy solar protons. Its output was sorted by an 8-level integral pulse-height analyzer. In the absence of information differentiating between particles stopping inside the scintillator from those traversing it, a detector such as this one has a double-valued response (Fig. 3). Information supplied by the other detectors in the experiment can be used to correct for the high-energy side of the response curve, although for solar events such corrections are usually quite small and therefore unnecessary. Thus this counter measured essentially the differential proton intensities in the low-energy region. Since the threshold of the first level was set considerably below the minimum ionizing level of about 450 keV (i.e. see Fig. 3), the counter responded to low-energy electrons as well. With the

available information from the other counters, and particularly from the single Geiger counter, it is possible to attribute, with reasonable certainty, the large increases in its counting rate to a specific particle component. Specifically, we can use this counter to gain information on electron fluxes in the vicinity of the earth's magnetosphere and for this reason will discuss in greater detail the response of the scintillation and Geiger counters to such electrons. In the course of this discussion it will become clear that considerable new such information can be obtained from an analysis of the corresponding counting rates during the lifetimes of the two mentioned satellites.

In estimating the threshold of the first level to individual electrons, we must take into consideration, in a straightforward manner, the thickness of the aluminum cover and the electronic threshold. However, when high electron fluxes enter the picture, the calculated threshold no longer holds. In Fig. 4 (a) and (b) we show the results of a calibration of this detector using the electron beam of a Van de Graaff accelerator. A Faraday cup was used to measure the number of electrons striking the detector. The dotted portions of some of the plots in Fig. 4 (a) correspond to regions where flux measurements could not be made, so that other means had to be used to estimate the fluxes involved. We believe that these estimates are within a factor of 2 of the actual flux values. On the basis of a response to individual electrons, we find that the detector used in the calibration should not have responded to electrons with energies below about 140 keV. Nevertheless, a brief examination of the results discloses the following facts. 1) Monoenergetic electrons with an energy as low as 40 keV were

detected when fluxes were sufficiently high. 2) The counter's efficiency appears to rise sharply above an electron energy of about 60 or 70 keV. 3) This efficiency is heading for its limiting value of 1 as the electron energy increases and the fluxes decrease. The last observation is obviously expected. The detector obviously responds to electrons with energies below the calculated individual particle threshold through pulse pile-up. As for the sharp increase in the efficiency, it is most likely related to the fact that the thickness of the shield is approximately equal to the range in aluminum of a 65 keV electron. Thus, electrons having an energy in excess of 65 keV have a good probability of penetrating this aluminum cover and accounting directly for the light produced in the scintillator. On the other hand, electrons below this energy can only be detected through the bremsstrahlung which they may produce when they stop in the aluminum. The abrupt change in the efficiency apparently indicates the point at which the lower order process begins to dominate. The results of this calibration bring out two important points regarding this detector. We notice first that the latter is non-linear as regards electron fluxes so that it does not constitute a particularly suitable device for absolute flux measurements. On the other hand, the sharp rise in its efficiency above an electron energy of about 65 keV considerably narrows the energy interval which includes an effective energy threshold for this counter. The other point is that, as Fig. 4 (b) shows, this detector is quite sensitive for electron energies above 65 keV and this high sensitivity is the basis of some important capabilities which we will discuss shortly.

Next we shall consider very briefly the Geiger counter whose data we are also using in interpreting the first-level counting rate. This counter is a halogen-filled, disc-shaped device, with an active region 4.45 cm in diameter and 1 cm thick. Its energy thresholds for electrons and protons are about 2 and 24 meV respectively but it can also respond to lower energy electrons through the bremsstrahlung which they produce in its walls, although with a much lower efficiency than the scintillation counter. As in the previous case, a calibration was conducted using the monoenergetic electron beam from an accelerator. These results are shown in Fig. 5. Since no pulse pile-up is involved in this case, it is expected and indeed observed that the counting rate varies linearly with flux, for a given electron energy. This calibration reveals that data from this counter are essentially of no importance when considering energies in the vicinity of 70 keV. However, these data are definitely essential in setting an upper limit on the energy of the electrons which make up the dominant contribution to the counting rate of the first level.

Returning to the scintillation counter, we shall first attempt to establish an approximate energy threshold in connection with the first-level response to electrons in the magnetosphere. This threshold will obviously depend on both the fluxes involved and on the energy spectrum of these particles. Measurements of this nature have been made recently [Montgomery et al., 1965]. It was found that the low-energy portion of the integral spectrum can usually be fitted reasonably well by a power-law curve, with exponents around -3 or -4.

Using this information along with the absolute fluxes given in the above reference, we find that the dominant contribution to the first level's counting rate will come from electrons in the 80-100 keV energy range. Consequently, we conclude that an effective threshold for this detector will be in this range. A word of caution is necessary however, since it is perhaps possible that processes such as electron bunching due to local wave motions, may be instrumental in increasing the importance of the lower energy electrons [Scarf et al., 1965].

We next consider some additional features of this detector which stem mainly from its high sensitivity to energetic electrons. This sensitivity can be used to advantage in obtaining 1) the time resolution needed when studying the highly variable characteristics of electrons in the outer magnetosphere, and 2) the necessary directional capabilities for detecting whatever observable anisotropic features these particles may possess. This is because, the collection time for each data point can be made quite small without introducing problems in connection with the statistical significance of individual readings. In this case however, both the collection and the repetition times, were determined from considerations affecting the entire cosmic-ray experiment and not the electron detecting capabilities of the scintillation counter. Thus data from each energy level of this counter were collected for 1.6 sec., once every 26 sec. The last figure obviously sets the lower time limit on the observable flux changes, when using data from individual levels of the counter. Later we will see that this resolution is quite adequate for many magnetospheric

observations. Regarding the directional capabilities of this detector, we note that it is located in the payload with its view centered at right angles to the satellite spin axis. Such a location is suitable for providing some information on the directional characteristics of the detected particles, provided certain other requirements are met. For instance, we obviously must have some means for determining the orientation of the detector as a function of time. Other requirements are that the detector must have a limited acceptance angle and that the data collection time must be considerably shorter than the satellite spin period. Fig. 6 shows a diagram of the scintillation counter. We see that its angular opening is limited by an aluminum collimator which however, still leaves a rather large solid angle of about 1 sr and an opening angle around 65 deg. With regard to the rate of spin, only Explorer XIV eventually attained a long enough spin period to allow information on spatial anisotropies. This came about after 3 to 4 months of precession which set in after launch and which finally stopped, amidst a continuous decrease in the total rate of spin, as shown in Fig. 7. Solar radiation pressure is believed to have caused this spin behavior, as it acted on the alternately pitched solar paddles of the spacecraft. Finally, a solar sensor provided the necessary information giving the orientation of this counter as a function of time. Thus there was an extended time period in the lifetime of Explorer XIV during which the requirements listed above in connection with the directional capabilities of the scintillation counter were satisfied.

In summary, we have seen that the magnetospheric measurements conducted with Explorers XII and XIV can supply 1) estimates on the fluxes of electrons in the energy region around 100 keV; 2) the time histories of these electrons with a resolution of the order of .5 min; 3) any detectable directional information pertaining to these particles, such as anisotropic fluxes due to trapping in a magnetic field, etc. It is of interest to mention the fact that a detector whose response to low energy electrons bears some resemblance to the above description of this counter was flown aboard the IMP-1 satellite and measured what were interpreted as fluxes of electrons with energies above 30 keV [Fan et al., 1964]. In this case, the shield was thin enough to allow such particles to reach the sensitive area of the detector. Pulse pile-up was again an important factor since the detector's response was extended to electrons with energies considerably below its electronic threshold.

As a final word about the operating stability of this detector, flight calibration data were provided continuously by a small  $\text{Pu}^{239}$  alpha-particle source mounted in front of the disc-shaped scintillator. The pulse-height spectrum of this source in CsI is sharply peaked and the position of this peak determines the thresholds of the various channels. Flight data indicated that the first level electronic threshold of the counter aboard Explorer XII remained reasonably stable after an original setting at about 120 keV. On the other hand, the same threshold of the detector aboard Explorer XIV displayed a continuous drift which must be taken into consideration when we analyze the data. Thus Fig. 8 shows in this case, that the

first level threshold increased by about a factor of 3 during the lifetime of this satellite. We may mention that this gain shift took place at a time when the intensities of trapped electrons in the path of the satellite had been enhanced due to the injection in the trapping region of  $\beta$ -decay electrons from the fission fragments of the "Starfish" nuclear explosion which took place on July 9, 1962 [Brown et al., 1963; Van Allen et al., 1963]. These electrons are believed to have been a major factor in this gain reduction. Because of the complicated response of this detector, it is not immediately clear how this gain shift has affected the counting rate. The effect will obviously depend on the effective energy threshold of the detector, and therefore, on the electron energy spectra and the fluxes involved. Of great significance, of course, is not just the total energy of the electron but also the fraction of this energy lost inside the scintillator. A 3-fold increase in the electronic threshold of the detector simply indicates that a given pulse height will require an energy loss inside the CsI 3 time greater than it did originally. Thus, for electrons near 65 keV, the equivalent energies do not differ greatly, whereas, this difference obviously increases for more energetic electrons. From earlier considerations regarding the effective energy threshold of this detector, we conclude that, in all probability, the shift in its threshold did not result in a disproportionate change in the counting rate.

We can obtain some indication whether this was the case by comparing our data with the corresponding data of other detectors aboard the same satellite. Such a comparison was made using published data

from 5 satellite orbits in the time interval from Oct 24, 1962 to July 11, 1963 [Frank, 1963]. Fig 9 summarizes the results of this comparison. Since the detectors whose counting rates we correlated have different response characteristics, we have made an effort to include in this plot only the data from outside the trapping region where the electron spectra are expected to be reasonably similar at all times. This plot shows that the two sets of data are uniquely related over the interval in which the threshold shift took place, thus, confirming what we have already concluded.

### III. DATA REDUCTION

Before ending this description of the experimental aspects of this investigation, it is appropriate to make a few remarks regarding some of the problems which we have faced in connection with the reduction of satellite data. Our primary concern in this case was to put the information contained in the counting rates of the scintillation counter's first two levels and of the Geiger counter into a form which would allow us to conduct a rapid but also accurate analysis of this information. The data were obtained in the following manner. The three levels named above, along with the seven additional ones, were connected with a 15-bit accumulator as shown in Fig. 10. Counts were collected in each level for about 1.6 sec., once every 26 sec., so that there was a 2.6 sec. interval between changing levels. After 12 complete cycles or a little over 5 min., there was a 2-min. gap in these data, during which time the data from the scintillation telescope were read out.

Digital computers have been used extensively in putting these data in the required form for plotting and for the other manipulations, and in calculating a number of spatial parameters characteristic of the satellite's instantaneous position during its orbit (i.e. magnetic latitude, longitude, sun angle, the corresponding quantities with reference to the ecliptic plane etc.). Noise problems have been frequent and are directly or indirectly responsible for large data gaps, particularly during the precession of Explorer XIV, when the

signal reception from the spacecraft became variable as its polarization changed from linear to circular and back to linear with changes in the aspect angle. A large portion of this data loss occurred during the digitization process and it is due to a number of factors such as timing errors, loss of synchronization, etc. Frequently, partial losses result from one or more missing digits from the 5 octal digits which make up each accumulator position. In addition, erroneous accumulator readings are often encountered and are usually eliminated by subjecting each reading to a number of tests incorporated in the computer program which handles these data. The counting rates of the scintillation counter's second level and of the geiger counter have been averaged over 7-min intervals before plotting to somewhat reduce the large volume of these data. The first level data however, are filled with large, short-term fluctuations, so that averaging is not particularly helpful in this case. Nevertheless through the use of fast automatic plotters, it has become possible to present in a reasonably short time, a complete and accurate history of the first level counting rate, during the lifetimes of the two satellites. Fig. 11 shows the inbound pass of Explorer XIV, on Jan 3, 1963. We have plotted (point-by-point) the first level counting rate versus universal time. Line plotting has been interrupted whenever consecutive points are two or more min apart along the abscissa. Thus, every 5 min we see the expected 2-min gap which is in addition to other gaps resulting from noisy data. The plotter has also been programmed to interrupt line plotting when consecutive points are more than one order of magnitude apart along the ordinate. For, in attempting to minimize

the loss of information due to noise in the data, we have considerably relaxed the tests applied to validate these data. Thus, we are frequently faced with the problem of isolated points which, when traced back to the raw data, are easily shown to be in error but which are included in our plots for the reason stated above. In general, it is quite easy to recognize such errors during the analysis of the data.

Another point of interest which this figure demonstrates is the upper limit in the counting rate corresponding to the capacity of the accumulator. When this rate exceeds 32,767 counts/1.6 sec, or multiples of this number, the accumulator is reset. Thus it is often possible to estimate much higher counting rates, simply by making use of the characteristic pattern which the first level plots assume when high counting rates are involved. For example, a closer look at the plot reveals that at about 0910 UT, the counting rate is approximately 96,000 counts/1.6 sec. We may finally mention that all first level plots have been prepared in the same manner to show the counting rate as a function of time. In addition, convenient orbital parameters have been included along the abscissa to facilitate the analysis of these data.

#### IV. THE SUNLIT MAGNETOSPHERE

Near the noon meridian, our electron data show an usually well-defined particle boundary, beyond which only occasional spikes in the counting rate are seen. This pattern is in substantial agreement with the observations of other investigators [i.e. Freeman, 1963; Anderson et al., 1965; Fan et al., 1964; Frank and Van Allen, 1964]. Fig. 12 shows the relevant data from a large portion of the Explorer XII orbit on Oct 8-9, 1961. In the three plots of this figure we show as a function of time 1) the integral counting rate (counts/1.6 sec) of the scintillation counter's first energy level, 2) the corresponding rate of the second level, averaged over 7-min intervals, and 3) the similarly averaged counting rate of the Geiger counter. Geocentric distance marks have been placed every 10,000 km along the abscissa, accompanied by the corresponding geomagnetic latitudes and the "magnetic sun-angles" (i.e. the projections of the satellite-earth-sun angles on the geomagnetic equatorial plane). When referring to these angles, we follow a convention by which positive values ranging from 0 to 180 deg. indicate a satellite position in the dawn side of the magnetosphere, while negative angles in the range from 0 to -180 deg. indicate that the satellite is in the afternoon side. This convention is demonstrated in Fig. 1. The background counting rate of the first as well as of the second levels is due for the most part to calibration alpha-particles and to cosmic rays. Both the outbound and the inbound passes in the above figure, are suitable examples of what we refer to as a well-defined particle boundary. It is seen

that neither the second level nor the Geiger counter begin to indicate any enhancement of particle fluxes until the satellite is well inside the magnetosphere. Reference to our earlier discussion of these detectors results in crediting the initial increase of the first level's counting rate to low energy electrons. More specifically, we have already seen reasonable justification for this response being due predominantly to electrons with energies around 80 to 100 keV. We should mention, however, that in all cases in which we have attempted to compare our data with the 40-keV electron data from the experiment flown on the same satellite by the State University of Iowa, we have seen similar histories between the two counting rates, so that the energy threshold of the detector is apparently not a major issue for much of our discussion.

The relative behavior among the counting rates of each of the three levels shown in this figure, is very typical of all the cases which we have examined up to the present, except for the few situations when cosmic rays enter the picture. For this reason, we will refer to the first level data from now on, as indicating low-energy electron fluxes, without making specific reference to the other two levels, unless such reference is made for other purposes. Assuming now that the observed particle boundary signifies the termination of trapping in the earth's field, we may consider a number of observations concerning the nature and location of this boundary. Much of our work in the sunlit magnetosphere simply confirms previous findings so that, it may be used as a guideline in the interpretation of other observations, particularly in the dark magnetosphere.

We have observed that the rate at which the first level counting rate changes upon entering or leaving the trapping region, is very much dependent upon the degree of magnetic activity. A commonly used measure of this activity has been the Kp index which is indicative of world-wide magnetic field variations. Many correlations have been shown to exist between this index and various observational quantities. Of great importance, from our point of view, has been a positive correlation between Kp and the observed streaming velocity of the solar wind [Snyder et al., 1963]. The bulk velocity of the solar plasma will presumably have a major role in determining the nature of the outer edge of the magnetosphere. Another relevant correlation has been made by Freeman [1963] who found that the Kp indices are generally related to the low-energy electron fluxes inside the magnetosphere. Our observations which have a bearing on this topic are summarized in the following figure. In Fig. 13 (a) we see a case of a smooth and gradual transition from lower to higher counting rates, as we enter the magnetosphere. The 3-hour Kp indices during this time are quite low. On the other hand, the period in Fig. 13 (b) which corresponds to generally high Kp values, is seen to be characterized by sharp spikes and a rapid increase in the counting rate. The same observation pattern holds rather well in a number of other cases of sunlit hemisphere observations, especially for local times not very far from local noon. A more detailed study of this pattern would require the replotting of the counting rates as a function of distance instead of time as we are looking here for a spatial rather than a time dependent behavior of the observed counting rates. Therefore, we will at this time restrict our discussion of this trend to

the few qualitative remarks already made.

Turning now to another point, we have mentioned earlier that satellite data have shown that the radial extent of the magnetosphere near the noon meridian is almost identical with the extent of the region of ordered and dipole-like magnetic fields. Thus, it is reasonable to expect that charged particle trapping will terminate at about the same location where the abrupt field changes mark the position of the magnetopause. This, in fact, has been confirmed in a few cases [i.e. Cahill and Amazeen, 1963; Freeman et al., 1963]. On the other hand, the radial magnetic field configuration of the magnetospheric tail indicates that sustained or durable trapping in this region must terminate much closer to the earth than the extent of the geomagnetic influence. This too has been confirmed by previous observations [Frank, 1964; Anderson et al., 1965]. However, very little detailed information is available thus far regarding the location of the trapping boundary as a function of local time. In other words, it is not known just where the separation of the two boundaries takes place. We have extracted from our data the necessary information to map the observed particle boundary as a function of the magnetic sun-angle. Fig. 14 shows such a map containing data from the region within 10 deg. from the geomagnetic equatorial plane. Fig. 15 covers the remainder of the magnetic latitude range of our data, this being approximately from -40 deg. to +30 deg.

Before we elaborate any further on these plots we should note a few facts related to their construction. We have seen that in some cases, the identification of a unique particle boundary is rather

unambiguous. This is generally true near the subsolar point. However, as we approach the edges of the sunlit hemisphere, we find an increase in the occurrence of cases not identified with a well-defined termination of particle fluxes. Such cases are usually correlated with disturbed conditions and are not included in these two plots. Furthermore, we like to emphasize that, although in many cases we are able to identify the particles inside the boundary as being trapped, from the spin-modulated counting rate, there are occasions when such an identification cannot be made. This is particularly true when this counting rate rises in a very short time from background to tens of thousands of counts per second. The spin modulation is also difficult to identify in data from Explorer XII due to its fast spin rate and in the data from Explorer XIV during the first 3 to 4 months of its lifetime. The use of spin modulation for the identification of trapped particles will be later discussed in greater detail, in conjunction with electron fluxes in the dark magnetosphere. At the moment, it will suffice to state that Fig. 16 is a typical example of a case which we claim, is characterized by spin modulation and by a unique particle termination, at a magnetic sun-angle of about  $-109$  deg. (i.e. at a local magnetic time of 19 hrs., 15 min.).

Returning now to Figures 14 and 15 for a closer examination, we make the following observations. We first notice that the data from the two satellites are fairly similar in those places where a spatial overlap occurs. This provides us with the necessary justification for this unified treatment which we are presently pursuing. We further observe that the equatorial data indicate that the quiet-time

trapped particles terminate at a well-defined average location throughout the sunlit magnetosphere. Near the noon meridian, the two plots are very similar, so that the particle boundary is least dependent on magnetic latitude in this region. As we move away from this meridian however, we see that the particle fluxes at higher latitudes generally terminate closer to the earth. This latitude dependence is evidently reflected in the large scatter of points in the plot of Fig. 15, since the latter includes data from a larger latitude range. Other observations pertaining to the dark magnetosphere will be discussed later.

We try next to determine the extent to which the particle boundary of Fig. 14 is identified with the equatorial shape of the magnetopause, as determined by local magnetic field measurements and by available theoretical treatments. Such treatments were for the most part based on the assumption that the solar wind interacts with the earth's field as a free molecular flow. The validity of this assumption is now seriously in doubt but it so happens that the pressure distribution near the subsolar or stagnation point has the same form whether the solar wind interacts as a coherent medium or as a stream of independent particles [Axford, 1962]. For this reason, it is expected that the shape of the actual boundary in this region will not be very sensitive to the particular interaction mechanism involved.

We choose first for comparison with our data the shape of the magnetopause from the work of Mead and Beard [1964] normalized to approximately  $10.8 R_E$  at the noon meridian. In Fig. 17 we superposed this shape on our equatorial data from the sunlit magnetosphere.

We note that no corrections have been applied to these data. The agreement shown by this plot is very good. The apparent discrepancy near the dawn meridian is artificial because, the available equatorial data in that region are such as to exclude the larger distances. In Fig. 18 we superposed the same magnetopause shape on the higher latitude data. This is done to show that near the subsolar point the fit is good once again but that away from it the latitude effect becomes quite evident, more so than one could explain in terms of the latitude dependence of the theoretical magnetopause.

Regarding comparisons with local magnetic field measurements, we have at our disposal a few cases of magnetopause crossings as indicated by data from the onboard magnetometer, as well as data from a greater number of such crossings by the IMP-1 satellite [Ness et al., 1964]. However, it is clear that the latter data can only be used as a group. From the few cases in which comparisons between nearly simultaneous magnetic field and particle measurements were possible it became obvious that within the accuracy of our plots, trapped electrons near the equatorial region terminate at locations which are identical with the corresponding magnetopause positions, in agreement with the few previous observations to which we have referred. The IMP-1 data on the other hand, have shown that the location of the magnetopause between the noon and dawn meridians is in good agreement with theoretical shapes such as the one from the work of Mead and Beard which we have used. What remains, therefore, is a direct comparison between our particle boundary near the equatorial region and the IMP-1 results which are shown in Fig. 19. We note that, since no effort

was made to apply any corrections to our data, we have made use of the similarly uncorrected results from the above reference. However, the comparison still requires that our data be replotted on the ecliptic plane in order to be consistent with the plot of Fig. 19. A combined plot resulting from the two sets of data is shown in Fig. 20. We may mention that the magnetic field data contain no latitude selection. It is not known however, if such a selection would have resulted in any changes in the average location of the boundary which they define. As it is, the agreement between the two sections of Fig. 20 is quite good.

Summarizing the results of this section, we note that we have obtained rather substantial evidence to the effect that the quiet-time equatorial trapping region has a well-defined average termination extending out to the boundary of the magnetosphere throughout the sunlit side. We have shown in a qualitative manner that the rate of the transition of the electron fluxes near this termination appears to correlate with the Kp index. Regarding dependence on magnetic latitude, we have seen that the surface bounding the trapping region appears to be in the form of a spherical cup near the subsolar point, with an increasing trend of the electron fluxes to assume a wedge-like shape away from this point. Finally, there appear to be no large asymmetries (if any at all) about the noon meridian in the trapping region of the sunlit magnetosphere. The apparent dawn-to dusk symmetry of trapped particles in the sunward side implies that, some recently observed asymmetries in connection with magnetospheric electrons at about 17 Re [Montgomery et al., 1965] apply probably only to transient

electrons which are frequently encountered in the transition region and in the tail of the magnetosphere.

## V. THE DARK MAGNETOSPHERE

### A. The Extent of the Trapping Region.

Looking once again at Fig. 14 we find that we were able at times to specify a particle boundary in the dark magnetosphere. We can state that generally, no such particle termination can be seen except on very quiet days. That is, the dark magnetosphere conditions appear to be strongly dependent on the degree of magnetic activity. We can demonstrate this with appropriately chosen satellite passes; Fig. 21 shows the Explorer XIV inbound pass of January 6, 1963. This day was exceptionally quiet. The daily sum of the 3-hr Kp indices was just  $0^+$  [Lincoln, 1963]. We see that the location at which the observed electron fluxes terminate is rather unambiguous, occurring near 13 Re, only 20 deg. from the magnetic midnight meridian. As the satellite approaches the earth from this point, the counting rate is characterized by a periodic structure which is superimposed on a gradual and continuous increase. This fine structure is caused by trapped particles which, as is well known, have unequal intensities at various angles to the magnetic field vector about which they spiral. Since the scintillation counter is mounted on a plane perpendicular to the satellite spin axis, we would expect to see this anisotropic feature (whenever it exists) provided that the spin axis is not nearly aligned with the magnetic field.

Fig. 22 shows another case when trapped particles appear to extend out to 12 Re, at a magnetospheric location less than 10 deg. from magnetic midnight. These data are from the inbound pass of February 4, 1963, at a time when Kp was never above  $0^+$ . Unfortunately, large data gaps

obscure the particle picture beyond about 12 Re. Nevertheless, this pass provides additional evidence that the trapping region in the dark magnetosphere does on occasion extend to distances beyond the corresponding average boundary location of the sunlit side.

We can further convince ourselves that we are detecting trapped and not streaming particles by correlating the first level counting rate with data from a sun sensor aboard the same satellite. These give us directly the orientation of the scintillation counter in relation to the plane defined by the satellite spin vector and the satellite-sun direction. Fig. 23 shows the correlation for a 5-min. interval, just after the satellite entered the region characterized by the spin-modulated counting rate, during the February 4 pass. We may note that, because the time elapsed between successive data points exceeds the satellite spin period, the sequence in which points appear in this plot is not the same as the order of their acquisition. This allows a positive identification of time variations in the counting rate, as compared to those variations which show a dependence on solar aspect. We clearly see in the figure, as we have already anticipated, that the observed counting rate is strongly dependent upon the solar aspect angle, i.e., the angle between the detector and the reference plane mentioned above. If the anisotropic features of the counting rate result from particles streaming preferentially in one direction, we cannot expect any periodicity with a period other than the satellite spin period. On the other hand, a spatial anisotropy which is attributed to trapped particles will usually be characterized by axial symmetry about the direction of the magnetic field. This means that the features of a plot such as the one shown in Fig. 23,

will repeat every 180 deg., which indeed is the case. Experimental evidence has shown that stably trapped particles have fluxes which have peak values at right angles to the magnetic field vector and minimum ones along this field. Thus, if this situation exists, the angle at which we observe the minimum counting rate defines the plane of the magnetic field and the satellite spin axis. The minimum in the counting rate occurs when the detector crosses this plane, this position being the one of closest approach to this field. The field direction itself cannot be deduced from this information alone, but additional considerations are possible which furnish more clues regarding this direction. For instance, if we assume that the actual magnetic field vector lies in the calculated magnetic meridian plane (based on a simple magnetic dipole) through the satellite position, or to express it differently, that this vector has no azimuthal component, we uniquely specify its direction in space. This assumption should be especially valid in the case of the inbound pass of February 4, when the satellite remained for an extended period of time near the magnetic midnight meridian. This and other considerations will later be used to extract from trapped particle data whatever information we can, regarding the field and the particles in the outer edge of the trapping region, near the antisolar direction. Since this is the first time to our knowledge that trapped particles of this region have been identified out to such great distances, this information is of considerable value.

The above cases of electron fluxes during very quiet conditions may now be compared with data from a disturbed day, shown in Fig. 24 and taken from the Explorer XIV inbound pass of January 30, 1963, listed as

one of the five most disturbed days of the month [ Lincoln, 1963 ] . Here the counting rate has a completely different history; we see neither evidence of a sustained anisotropy nor any obvious termination of particle fluxes. Instead, the large and frequent variations shown in this figure strongly imply the existence of turbulent conditions. From the findings of Anderson et al. [ 1965 ], it is very likely that these conditions extend to distances beyond 30 Re. Thus, it appears that the region of the dark magnetosphere in which durable trapping occurs, decreases rapidly with increasing activity, giving way to highly variable conditions which, to some extent, may be indicative of the solar wind-geomagnetic field interaction.

We see yet a third picture, separate portions of which resemble each of the two previous cases. We illustrate this by presenting in Fig. 25 data from the inbound pass of Feb. 5, 1963, a relatively quiet day. This figure shows a clear transition from generally isotropic and transient to trapped electron fluxes, taking place when the satellite is between 8 and 9 Re, as it moves toward the earth. There is supporting evidence which implies the sudden hardening of the electron spectrum in coincidence with the commencement of trapping [Konradi, private communication ]. A similar, sharp transition into high and stable electron flux regions has been observed before with omnidirectional counters [Frank, 1964; Anderson et al., 1965 ]. We may point out, however, that the information presented here enables us to use a minimum of speculation regarding the nature of the particles from either side of the observed transition.

To summarize, we have seen that the extent of the trapping region in the dark magnetosphere depends to a large extent on the degree of activity.

On quiet days, trapped particles have been detected out to 13 Re, whereas, with increased activity the outer portions of the trapping region are replaced with what appear to be, isotropic and variable fluxes of softer electrons.

B. Particle Distributions and the Nature of the Trapping Field.

Having described the general characteristics of low-energy electrons encountered in the dark magnetosphere by Explorer VIX, we next reexamine those particular cases in which a visual inspection of the first level plot has revealed spin modulation, which in turn implies the presence of a spatial anisotropy. We may begin with the inbound pass of Feb. 4, shown in Fig. 22, assuming that the maximum counting rate is seen at right angles to the magnetic field. We will express all relevant directions in terms of the two convenient variables, the magnetic latitude  $\lambda$  and the magnetic sun angle  $\theta$  which we have previously defined. From plots such as the one shown in Fig. 23, constructed at various points along the satellite trajectory, we have established as a function of time the solar aspect of the detector at minimum counting rate as shown in Fig. 26. We have here what appears to be a transition taking place either in the magnetic field direction or at the angle with respect to this field at which the minimum counting rate occurs. We see little or no modulation in the interval between the different situations which exist from either side of this transition. As explained earlier, although our information is not sufficient to produce a unique magnetic field direction, we can effectively narrow down the range of possibilities by using some well-justified assumptions. The general tendency of the distant magnetic field in the tail of the magnetosphere to align itself along the earth-sun direction, suggests

that the most obvious assumption in this case, (i.e., so near the anti-solar direction) is that the magnetic field vector lies on a plane of constant longitude. Using this assumption along with solar aspect information and the known spatial coordinates of the satellite and its spin vector, we arrive at the field directions shown in Fig. 27(a). Each point in this figure represents a satellite position in a meridional plane, with a complete neglect of longitudinal changes. For comparison, we have included the corresponding directions of an undistorted dipole field. It is quite obvious that the field directions deduced from the earlier aspect data of Fig. 26 are in large disagreement with any reasonable field configuration which we could expect in this region. On the other hand, the later aspect data from the second section of the same figure, result in a field orientation in much closer agreement with the undistorted dipole. The near-isotropic conditions in the region between the two sections are somewhat of a puzzle, since during this time, the spin vector and the dipole field are nowhere near alignment, yet the observed modulation of the counting rate goes through a minimum at this point.

In an attempt to gain better understanding of these observations, we now turn to similar data from the inbound pass of Jan. 9 shown in Fig. 28. This pass is of particular interest to us because data from the onboard magnetometer have been made available for the appropriate time interval [Cahill, 1964; R. Kaufmann, private communication]. The direction of the local field is contained in two angles, of which the angle  $\psi$  is the angle between the spin vector-sun direction plane and the spin vector-magnetic field vector plane. If our basic assumption regarding the direction relative to the magnetic field vector at which the maximum

particle flux is observed, is correct, then the solar aspect angle pertaining to the scintillation counter's direction at minimum counting rate is identical (or differs by 180 deg.) with this angle  $\psi$ . This provides us with the opportunity of a direct comparison between the particle and the corresponding magnetic field data. Such a comparison for the Jan. 9 data is shown in Fig. 29. The agreement is indeed poor but the discrepancy is almost constant and near 90 deg. throughout a 4 to 5-hour interval after the trapped particles were first observed during the pass. In fact, this comparison suggests that the solar aspect angle at maximum counting rate is very nearly identical with the angle  $\psi$  which, if shown to be correct, implies that throughout this interval, trapped particle fluxes peak essentially along the field lines. This would certainly explain the lack of any agreement in our effort to deduce the direction of the field at the outer portion of the trapping region in the dark magnetosphere. We must now show that closer to the earth, in regions where past investigations have shown trapped particle fluxes peaking at right angles to the magnetic field, our minimum counting rate solar aspect is near agreement with the corresponding  $\psi$ . Unfortunately, the Jan. 9 data, after about 0920 UT, are missing. Thus, a comparison with magnetometer measurements closer to the earth is not possible in this case. However, somewhat of a similar situation exists during the previous inbound pass of Jan. 7, for which magnetometer data are also available. Only, spin modulation is not seen here until after 2045 UT, when the satellite is at about 8 Re geocentric distance. At this time, the solar aspect at minimum counting rate is again 80 deg. to 90 deg. out of phase with the corresponding  $\psi$ . Data at 2218 UT and

about 6 Re, however, are in very good agreement with both the dipole field (based on a normal pitch-angle distribution) and with the magnetometer data.

The last example of this type of particle behavior, and perhaps the best illustration of what appears to take place, is provided by the Jan. 6 inbound pass shown in Fig. 21. The orbital parameters of the satellite during this exceptionally quiet day are almost identical with the corresponding information of the Jan. 9 pass. We may therefore expect some similarity in the magnetic field situation, at various points along the satellite path, between these two orbits. We will assume this to be the case, since no magnetometer data have been made available for the Jan. 6 orbit. In Fig. 30 we show the solar aspect angle at minimum counting rate, as a function of time. The dotted portion of the plot corresponds to the well-defined segment in Fig. 21 where a minimum of spin modulation is seen. Just as in the Feb. 4 case, we again see roughly a 90 deg. change in this angle, taking place across this region of near-isotropic conditions. The sections of the plot immediately preceding and following this dotted portion are in good agreement with the data of Fig. 29 and the interpretation we have given to them. Apparently, were more data available on Jan. 9, we would have seen a similar transition at that time into angles in close agreement with the magnetometer data. This is well supported by the fact that the observed percentage of spin modulation during the Jan. 9 pass is rapidly decreasing (see Fig. 28) just before the data are interrupted.

In reviewing the last few examples of anisotropic fluxes due to trapping, we see rather strong evidence to the effect that electrons

trapped in the distant geomagnetic field and near the midnight meridian have distributions with peak values along the field lines instead of the more usual case of a maximum flux at right angles to the magnetic field, which is known to dominate the picture closer to the earth. We have also seen that the changeover from the one type of distribution to the other takes place across a region located at about 7 to 8  $R_E$  at small angles to the equatorial plane, and characterized by near-isotropic conditions. We find some evidence that this region tends to move inward with increasing activity.

Returning now to our previous attempt to extract magnetic field information from trapped particles, we replot in Fig. 27(b) a new set of field directions for the points of Fig. 27(a), after making the necessary corrections in our assumption regarding the direction of the maximum particle flux relative to the magnetic field vector. These changes of course do not affect the three inner points of the previous plot. We see that the new field directions imply an almost radial field, something that is certainly acceptable in view of the spatial region involved. The small, near constant angle which this field makes with the geomagnetic equatorial plane could be a consequence of the oblique incidence of the solar wind at this time, which will undoubtedly affect the position of the effective equatorial plane at large geocentric distances. On the other hand we must remember the approximate nature of these deduced field directions, since the concept of a constant longitude field is probably only partially correct at these large distances, even at small angles to the antisolar direction.

We may also attempt to extract similar magnetic field information from the Jan. 6 and 9 data. Here, however, we are somewhat removed from the midnight meridian and the constant longitude assumption is certainly open to considerable doubt. We approach this problem in a different manner. From all possible field directions consistent with our data, we may look for the direction closest to the undistorted dipole. This will provide us with some indication regarding the minimum distortion from the dipole shape, which we can expect the actual field to have, and with the probable form of this distortion. In Fig. 31(a) we show the meridional view of this closest approach field corresponding to the Jan. 6 data, as summarized in Fig. 30. Again, the dotted arrows indicate a generally "stretched" field which can be almost in complete agreement with the direction of the dipole as we go to smaller geocentric distances. The four points which do not follow this description may simply indicate that at these locations, the maximum in the pitch-angle distribution is not along the field lines, as it was assumed to be. However, we can also point out that the appearance of the field in these points is as if we are crossing an effective magnetic equatorial plane, something which must certainly be considered in view of the large negative magnetic latitude of the subsolar point. We will return to these points after examining next the equatorial view of this field. This view is shown in Fig. 31(b) along with the corresponding magnetic longitudes of the undistorted dipole. Here again, with the exception of the same four points, (the first point actually is not included in the figure), we see that the minimum possible deviation from the direction of the dipole increases with geocentric distance, the general tendency being

for the field to align itself with the earth-sun direction. Again, almost complete agreement with the dipole becomes possible at the innermost points.

Regarding now the points which do not fit in this picture, it is strongly implied by the plot in Fig. 31(b) that acceptable longitudes of the field in these points should be much nearer the midnight meridian. If we assume that this is the case and replot Fig. 31(a) after changing the field directions of the four outermost points accordingly, we get the plot in Fig. 31(c). It is clear that the change from the previous meridional view is almost insignificant. This is an indication that in this case, the latitude of this closest approach field is weakly dependent on the choice of the corresponding longitude. Thus, the field behavior displayed in these four points is very likely real and we therefore believe that we are crossing the effective equatorial plane which is displaced from that of the undistorted dipole because of the oblique incidence of the solar wind. In support of the above observations, the meridional and equatorial views which fit the Jan. 9 data are shown in Fig. 32(a) and (b). In this case all points are consistent with a field deformed in the manner described above.

Summing up the above results concerning the direction of the geomagnetic field in the dark magnetosphere, as deduced from trapped particles, we have seen evidence implying that, at the outer edges of the trapping region and near the equatorial plane, the field shows a tendency - which increases with distance - to align itself with the earth-sun direction.

### C. Other Temporal and Spatial Characteristics

As was explained earlier, the first level counting rate pertaining to stably trapped particles usually exhibits a periodic behavior with a period equal to one half the satellite spin period. Thus, we can fold a plot such as Fig. 23 on itself, by adjusting aspect angles over 180 deg., so that all angles in the plot fall in the range between 0 and 180 degrees. In fact, this will give us some indication whether the expected symmetry does indeed exist. This we have done in Fig. 33 with data from two appropriately chosen time intervals from the Jan. 9 inbound pass. Considering first the plot in the figure which corresponds to data obtained at 0731 UT (this is the mean time of the 5-min. interval), we see no apparent distinction between the group of points corresponding to angles which we have adjusted and the remaining points in the plot. We interpret this as an indication that there is no sustained net flow of electrons on a time scale that we can detect (of the order of a few minutes or higher) or in a direction that we can see. This plot is representative of practically all cases of trapped particles which we have thus far examined. Deviations from the expected smooth curve are often seen, but usually they do not indicate a sustained preferential flow. We have found however, what appears to be just one example of such flow, at a geocentric distance of 11.5 Re, which we show as our second example in the above figure. The usual symmetry about 180 deg. appears to be absent. The points of this plot were obtained in time, in the order shown in the figure, from left to right, so that the effect we see here cannot be explained as a change in time. If what we see is

indeed a preferential flow, the latter is consistent with a higher electron flux directed away from the earth. This implies the existence of an acceleration mechanism inside the location of the satellite when these data were obtained. It is of interest that this example occurred outside the region where, according to our data, pitch-angle distributions of trapped particles tend to isotropy, and at a time when electron fluxes were peaking along the magnetic field lines.

The greatest portion of dark magnetosphere data in our possession involves electron flux patterns similar to those we have seen in Fig. 24. Although such fluxes exhibit no obvious anisotropic features, we must nevertheless explore the possibility that such features may exist in a somewhat less obvious form. They may for example result from particles streaming along the highly aligned magnetic field lines of this region. In fact, preliminary results of particle measurements carried out with the circularly orbiting Vela satellites, have indicated support for the existence of such streaming [Asbridge et al., 1965]. Since the magnetic field alignment is more or less along the earth-sun line, we may look for possible enhanced electron fluxes at small angles to the two opposite solar aspects defined by this line. In Fig. 34 we show all data points from the inbound pass of Jan. 24 within 20 deg. of 0 and 180 deg. solar aspect. At the starting point of this plot, the satellite is located at a distance of about 100,000 km and very near the midnight meridian. Its spin vector makes an angle of 52.5 deg. with the earth-sun direction. In view of the large acceptance angle of the scintillation counter, this angle is believed large enough to allow the detection of particles streaming along the field lines, if such streaming really takes

place. The two superimposed plots of the above figure show no evidence of sustained streaming. Several other cases, including some when the spin vector was more orthogonal to the earth-sun direction, have also been examined with likewise negative results. Additional directions have been similarly probed but no evidence has been seen supporting the existence of anisotropic features among the seemingly isotropic fluxes of tail electrons.

One consistent feature of electron fluxes outside the trapping region is the appearance of characteristic "patches" of these particles which, for the most part, have a fast onset and a slower decay for both inbound and outbound passes. This has also been observed by Anderson [ 1965] who therefore suggests that these fluxes are not really spatially stationary as our reference to them as patches may imply. We believe that the initial fast rise in the counting rate has physical significance in that it is probably related in some manner to the mechanism by which these particles suddenly find themselves throughout the region surrounding the satellite. Such a mechanism may result from an instability (as Anderson and others have suggested) or perhaps could be a direct result of a sudden change in the solar wind characteristics. In any case, we will use this easily distinguishable onset to investigate the dependence of these tail electrons on the magnetospheric variables.

Fig. 35(a) shows the number of fast-onset events within 30 deg. from magnetic midnight, as a function of magnetic latitude. Data below about 8 Re were not included in this plot. In our arbitrary classification, an event is characterized by an increase in the counting rate, exceeding one order of magnitude within 3 minutes. We also require that the mean

width of the resulting pulse is greater than 10 min. The data were normalized to take into consideration the unequal probabilities of occurrence of the various magnetic latitude intervals due to data gaps and to the particular type of satellite orbit which we have in this case. The plot shows that these events tend to be more abundant near the geomagnetic equatorial plane. Unfortunately, the lack of sufficient data from positive latitude regions precludes an exact determination of the plane of symmetry. Even so, it appears that magnetic latitude is a far more appropriate variable to use in describing the topology of electron fluxes in the magnetospheric tail (at least up to 16 Re) than are the ecliptic and solar magnetospheric latitudes (see for example, Frank, [1964] and Ness, [1965] ). This conclusion is consistent with recent electron observations at about 17.1 Re with a Vela satellite [Montgomery et al., 1965 ].

The corresponding dependence of these electron events on geocentric distance is next being sought; Fig. 35(b) shows the resulting plot. We have again normalized the data to make all distance intervals equally probable. We see that such events appear more frequently at about 11 Re than at larger distances. For example, their frequency drops by nearly a factor of 5 as we go from about 11 to 16 Re. This result is in good agreement with a similar conclusion by Anderson [1965] . The observation that these events become less frequent below 11 Re can probably be attributed to the fact that this region is often occupied by trapped particles and is therefore void of the unstable features characterizing our events.

## VI. CORRELATIONS

The transient fluxes of low energy electrons which we have encountered outside the trapping region of the dark magnetosphere, and which become enhanced on disturbed days, are undoubtedly related at some time during their history to the particles precipitating into the earth's atmosphere to cause aurorae, increased radio noise absorption and other related phenomena. Magnetic field variations, particularly near the auroral zone, should likewise be representative of conditions existing in the magnetosphere, the same conditions which are probably instrumental in accelerating these electrons. Thus, it is reasonable to expect some degree of correlation between the precipitating electrons (and the phenomena resulting from them) -- as well as magnetic field variations at auroral stations -- and the electrons in those characteristic patches in the tail of the magnetosphere.

It is clear however, that the probability of finding such a correlation will depend greatly on the size of the spatial regions involved in the acceleration and propagation of these particles and, equivalently, in the generation and propagation of the corresponding magnetic disturbances. In general, localization of any of these processes will drastically reduce our opportunities of finding the observation points at favorable positions for correlations to occur. Phenomena directly dependent on particle precipitation are of a more local nature than ground magnetometer observations. This fact may well be reflected in the findings of the following attempt to compare

the first level counting rate with magnetic and radio noise absorption records of a number of auroral stations and with a few available data from lower altitude satellites.

Early in this phase of data analysis, it became apparent that no significant correlation existed between our electron data and ground magnetograms from low latitude stations. For this reason, the bulk of our observations have come from the magnetic records of stations near or in the auroral zone. Large portions of the data in the period of interest, from College and Barrow Alaska, from Kiruna Sweden, Leirvogur Iceland and from Byrd Station in the Antarctica, have been examined. Fig. 36 is typical of our findings. It shows several cases of abrupt counting rate increases in our data being nearly coincident with corresponding changes in the magnetograms of stations from the above list. Our observations may be summarized as follows: Cases such as those shown here are not infrequent. They involve for the most part, the horizontal component and the declination of the magnetic record. They tend to favor smaller geocentric distances. Correlations are generally at their best at the leading edges of the nearly simultaneous changes in both sets of data. Usually, neither are the widths of these pulse-like events in close agreement, nor is the correlation extended over long intervals of time, even if additional electron peaks appear in the data. Finally, a detailed comparison between the relative positions of the satellite and the ground station has failed to show any consistent pattern. Thus, it appears that the particle acceleration which our sudden counting rate increase implies, and the magnetic disturbance recorded by the station, occur within at most a few

minutes of each other and are phenomena which most likely involve large magnetospheric regions at a given time.

A few related observations have been reported before. Fan et al. [1964] have observed a correlation between electron peaks in the transition region in the sunlit hemisphere and the degree of the disturbance of the geomagnetic field. On the other hand, Ness [1964] has observed a sharp drop in the magnitude of the local magnetic field, occurring almost simultaneously with a corresponding increase in the observed flux of tail electrons, as seen by detectors aboard IMP-1.

We next turn our attention to a few riometer records which we were able to compare with our first level data. The majority of these came from three neighboring stations in Alaska, that is College, Healy and Fort Yukon. A few records from Kiruna Sweden were also examined. Fig. 37 represents the best indication that we have obtained of a possible detailed correlation between increased radio noise absorption and enhanced electron fluxes in the magnetosphere. The lack of a more positive result can be partly attributed to the small number of riometer records which we were able to examine and probably, to a larger extent, to the local nature of these data, as mentioned earlier. A good example of this is seen in the same figure where the three absorption traces are markedly different even though these stations are within .3 deg. of magnetic longitude and 3 deg. of magnetic latitude. Although detailed correlations are more rare in this case, just as with ground magnetograms, there appears to be a general agreement between the degree of absorption and the electron flux

levels observed in the tail of the magnetosphere.

The above remarks regarding our attempts to find correlations between our electron data and riometer records, apply as well to similar attempts involving direct measurements of precipitating electrons, by means of lower altitude satellites. A few measurements from the Alouette I satellite have been made available [McDiarmid and Burrows, 1965a] and generally show the existence of sharp, high-latitude "spikes" of electrons, a large portion of which apparently precipitate into the atmosphere. Although no direct comparison between these data and ours is possible because of the entirely different time scales involved, the appearance of these large low-altitude fluxes occurs at times of high first level counting rates.

## VII. SUMMARY

Data from nearly identical single crystal detectors aboard Explorers XII and XIV have been used to study several spatial and temporal characteristics of energetic electrons in the magnetosphere. Our findings may be summarized as follows:

1. (a) We have found that trapped particle fluxes near the magnetic equatorial plane, terminate at a well-defined average location throughout the sunlit magnetosphere, which is essentially identical with the location of the magnetopause as determined by local magnetic field measurements and by theoretical models based on the guidelines of the Chapman-Ferraro picture. Furthermore, we have seen that particle fluxes at higher latitudes terminate closer to the earth, the deviation from the above location increasing with the angular separation between the satellite and the earth-sun direction.

(b) We have presented evidence to the effect that the sunlit magnetopause is symmetric about the earth-sun line.

(c) We have shown that the structure of trapped electron fluxes near the boundary of the magnetosphere and at small angles to the earth-sun direction, is dependent on the geomagnetic activity, as determined by the Kp index.

2. (a) With regard to the dark magnetosphere, evidence has been presented to the effect that the morphology of electron fluxes there strongly depends on the degree of geomagnetic activity. Trapped electrons near the magnetic equatorial plane and the midnight meridian have been found to extend on quiet days to large geocentric distances,

exceeding 12 Re at times. On disturbed days on the other hand, highly variable and seemingly isotropic fluxes dominate the particle picture throughout the outer regions of the dark magnetosphere.

(b) We have presented data implying the existence of a region in the dark magnetosphere located on quiet days at about 8 Re near the equatorial plane, in which the pitch-angle distribution of trapped electrons tends to isotropy. While closer to the earth the maximum of this distribution occurs, as expected, at right angles to the local magnetic field vector, at greater distances it takes place along the field lines. We have seen implications pertaining to the inward displacement of this isotropic region on disturbed days and to the possible existence of an electron acceleration mechanism inside the trapping region.

(c) Magnetic field information deduced from the anisotropic features of trapped particles near the antisolar direction has been found to be consistent with a field generally "stretched" by the tangential stress exerted by the solar plasma, as contrasted to the compressed field of the sunward side.

(d) Regarding electron fluxes outside the trapping region, we have found no evidence of any sustained, detectable anisotropy, such as streaming in the direction of the magnetic field. These fluxes are characterized by drastic changes in the form of pulse-like events of various amplitudes and widths which, however, usually have a sharp leading edge and a slower decay. We have found that the intensity of these events increases during periods of high Kp, that they generally tend to cluster about the geomagnetic equatorial plane, and that the frequency of their occurrence decreases with geocentric distance.

3. (a) Sharp increases in the observed fluxes of magnetospheric electrons have been found to correlate with the onset of magnetic bays in the auroral zone.

(b) Similar correlations with the more localized phenomena of electron precipitation and the resulting increase in the absorption of radio waves are considerably more rare.

## VIII. DISCUSSION

We have presented a number of observations pertaining to electrons in the earth's magnetosphere. Most of these observations are in connection with the form and the location of the outer boundary of the trapping region which extends around the earth. Due to the anisotropic nature of the solar wind, we have found as expected, large differences between those results which pertain to the sunlit magnetosphere and the remaining results. Regarding our observations in the sunlit region, we find that most of them were not entirely unexpected as they have been implied by previous experimental and theoretical works. There are several interesting points however which need further discussion.

We have seen that the average location of the magnetopause near the equatorial plane is defined equally well by both characteristic changes in the local magnetic field and the termination of trapped particle fluxes. Furthermore the resulting equatorial shape of the magnetopause appears to be in good agreement throughout the sunward side with calculations based on the assumption that the solar wind can be treated as a flow of independent charged particles. It is somewhat surprising that this agreement extends to points near the dawn and dusk meridians, where deviations arising from the neglect of the coherent behavior of the solar wind could be expected. We further note that the results we have presented imply a generally stable boundary over the entire sunlit equatorial region. The apparent symmetry of this boundary about the earth-sun direction is certainly consistent with the IMP-1 results regarding the direction of arrival of the solar plasma. Its average location relative to the earth's center does

not appear to have changed appreciably in the elapsed time interval of more than two years between Explorers XII and XVIII (IMP-1).

Another point we would like to make is in connection with the noon-midnight asymmetry in the latitude dependence of the trapped particle fluxes. A similar effect has also been observed with lower altitude satellites, [i.e., Williams and Palmer, 1965] and appears as an inherent feature of some magnetospheric models in connection with the compression of the geomagnetic field near the subsolar point, due to the impact of the solar wind, and the stretching of the field lines in the dark region as a result of the shearing stresses attributed to this wind [i.e., Fairfield, 1964].

Turning our attention to the dark magnetosphere, we first note that we have found a number of occasions when quiet-day trapped particles were detected beyond 12 Re near the equatorial region. Assuming that durable trapping can only take place when the geomagnetic field lines are closed instead of extending out to large radial distances, we arrive at the conclusion that the closed portion of the dark magnetosphere can expand considerably near the equatorial plane, its radial extent on quiet days reaching distances well beyond 8 Re which is usually accepted as roughly representing the limiting extent of the trapping region in the dark magnetosphere. Magnetic field information deduced from the anisotropic features of trapped electrons indicates a highly distorted field (as compared to the simple magnetic dipole) having an almost radial appearance at the outermost portions of the trapping region, in agreement with the picture presented by local magnetic field measurements and with the existence of a neutral sheet in this general location [Ness, 1965].

One of the most interesting findings of this investigation is the evidence we have presented in connection with the pitch-angle distributions of electrons trapped in the dark magnetosphere. To our knowledge it is the first time that sustained trapping has been found in which particle fluxes appear to peak along the field lines instead of peaking at right angles to them. Considering the shaping of a given pitch-angle distribution, we see that it is determined by factors such as; fresh particle injection in the trapping region, changes in the energy of the already present trapped particles, and particle losses at some preferred direction relative to the magnetic field. The usual case of higher particle fluxes in a direction perpendicular to the field vector, which invariably represents trapped particle distributions at less remote regions [Pizzella et al., 1964] is a direct result of particle losses into the atmosphere. Such losses occur preferentially for particle velocities at small angles to the lines of force. Our results however indicate that trapping in the distant field of the dark magnetosphere may involve one or more additional considerations from those enumerated above. Thus we can account for the maximum of the distribution occurring along the field lines by assuming that electrons in the outer trapping region are accelerated or decelerated anisotropically as they spiral about lines of force and drift in magnetic longitude; or perhaps that they are being lost from this region, preferably at right angles to the magnetic field. Acceleration of course must take place somewhere in the magnetosphere, as is implied by a number of independent observations which, as we have seen, suggest the simultaneous appearance of large

fluxes of transient electrons over large magnetospheric regions. Whether the mechanism responsible for this acceleration is located inside (or at the edge of) the trapping region, or whether acceleration takes place entirely outside the body of the magnetosphere is not known at the present. O'Brien [1964] using data from the lower-altitude Injun 3 satellite has observed that increases in the fluxes of precipitating electrons take place at the same time that the trapped populations are being enhanced. In fact, he found that, during precipitation, fluxes tend toward isotropic conditions over the upper hemisphere. He has suggested that the necessary acceleration could be accomplished inside the trapping region by high-altitude temporary electric fields acting along the magnetic field lines. This suggestion is not inconsistent with our findings, although perhaps not the only one which can account for them. It is of interest however that we have seen one rather convincing case, where consistently more electrons were coming up the field line and away from the earth than were returning, which could therefore be considered as an indication that acceleration was taking place somewhere closer to the earth. Another indication of possible acceleration is the observed isotropy in the pitch-angle distribution occurring suggestively near magnetic shells which roughly correspond to the auroral zone. It is not difficult however to see that both a distribution with peak fluxes along the field lines and the isotropic conditions could be resulting from electron losses other than those which take place into the atmosphere. We have seen that the magnetospheric-tail region is characterized by frequent and drastic changes in the fluxes of

trapped electrons occurring on the very quiet days when the outward expansion of the trapping region was seen. Trapped particles, while traversing the nearly radial and weak field of the elongated magnetic loop near the equatorial region, are very likely under the influence of strong perturbations which can cause trajectory changes to the effect that appreciable leakage from the trapping region probably takes place at this time. Electrons with large equatorial pitch angles will tend to spend more time in this elongated field region and will therefore be more susceptible to such perturbations and eventual loss.

The above considerations imply that perhaps our reference to trapped particles in the distant field of the dark magnetosphere as "durably trapped" is not strictly correct. The observed temporal variations inside the trapping region, although small on quiet days, certainly indicate that electrons there undergo changes on a much shorter time scale than that which applies to the more conventional trapping of the lower latitude shells. Unfortunately, the fine structure of these changes is missing from our observations (except for the one case which we have discussed) because it is definitely beyond the capabilities of our detector. We believe that an improved time resolution will result in a larger number of cases in which preferential particle flow along magnetic field lines is seen, superimposed on the usual anisotropic pattern of trapped particle fluxes.

Additional information on the nature and the location of the acceleration mechanism which we are seeking, can be obtained from observations in connection with electron fluxes in the tail of the magnetosphere, which are clearly outside any sustained trapping. These particles

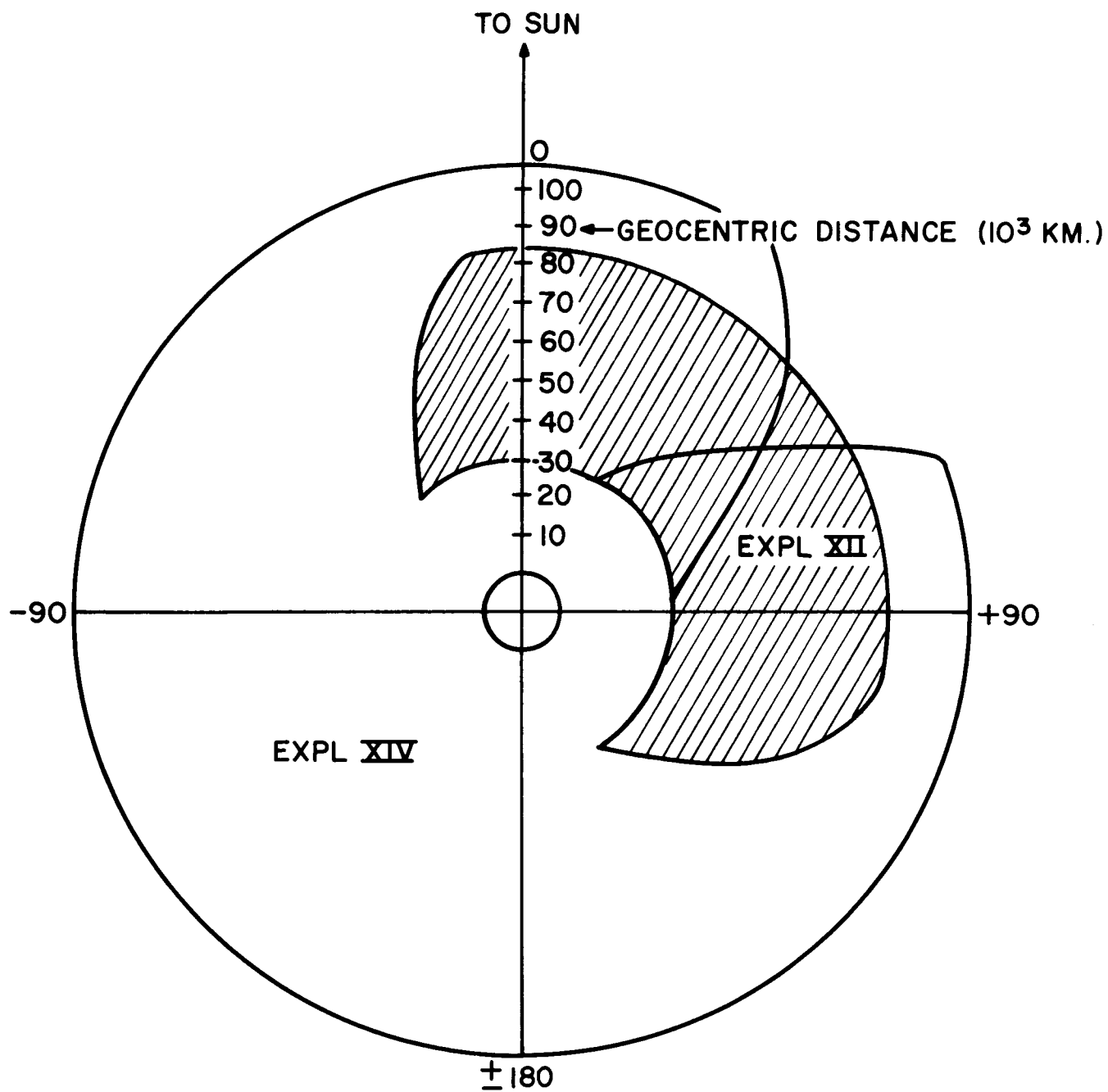
are essentially absent on quiet days when the observed trapping extends to large radial distances, but their numbers increase with the confinement of this trapping to regions closer to the earth. At times we have been able to see a rather distinct boundary between fluxes tending to isotropy and those which clearly displayed anisotropic features. We have also seen that a spectral change takes place across this boundary, with the trapped electrons having the harder spectrum. As mentioned before, we have little doubt that such tail fluxes have the same origin as the "fresh" electrons which O'Brien describes during a precipitation event and which McDiarmid and Burrows [1965a] detect as high latitude spikes in their counting rate. With regard to the generation of these particles, we believe that there are several indications that they are not locally accelerated but that they are the products of an acceleration mechanism located closer to the earth and very likely inside the trapping region. We first point out that this conjecture is consistent with our previous discussion in connection with observations on trapped particles. We may think of the characteristic "patches" or "islands" of tail electrons as being due to the combined contributions of electrons arriving almost directly from the source, which probably dominate the sharp rise of such events, and electrons which had undergone various degrees of trapping and which are leaking out of the just replenished trapping region. This explanation is at least consistent with the observed softening of the energy spectrum during the peak flux of a given event [Montgomery et al., 1965]. Such electrons may be quickly transported to large geocentric distances, either by streaming along field lines or by drifting

through the magnetic field with the bulk velocity of the medium [i.e., Jokipii and Davis, 1965]. Recent observations have indeed produced evidence of electrons streaming away from the earth and the sun [Asbridge et al., 1965]. It is surprising that our efforts to confirm such observations produced a negative result. Perhaps such streaming is energy dependent to the extent that it is detectable for 40 keV electrons and not so for energies in the range of 80 to 100 keV. Certainly some energy dependence is to be expected since sustained streaming implies the existence of ordered fields and this ordering may become effectively lost for electrons with large Larmor radii. The existence of an energetic electron source as assumed above is also consistent with the fact that electron events in the tail of the magnetosphere (as previously defined in this work) become less and less frequent as the geocentric distance of the observations increases. Regarding the observed difference in the energy spectra between trapped and transient electrons, it may well be due to the spectral changes which probably take place when the latter drift away from their source, while at the same time diffusing out of a given region within the moving medium, since the higher energy ones will tend to diffuse faster.

## IX. CONCLUDING REMARKS

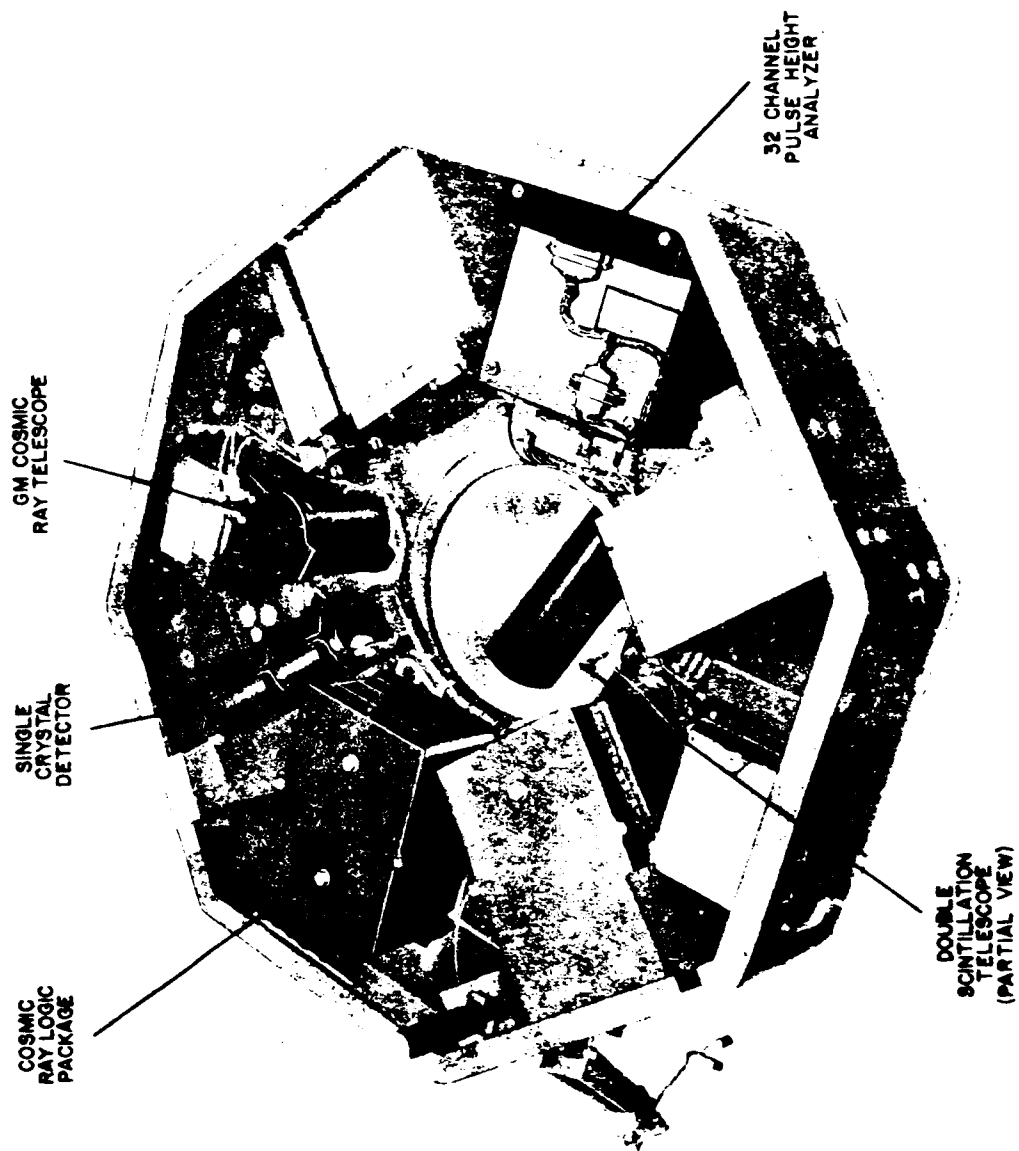
We have seen that, in agreement with earlier indications, this investigation has produced substantial evidence to the effect that the dark magnetosphere is the key to the physical processes which are the source of charged particles feeding the outer radiation zone and the relevant physical phenomena such as the aurora. We believe that more definite experimental information with regard to the nature and the location of these processes can be obtained with detectors and satellite orbits similar to those described here. Of particular importance will be additional data in connection with the pitch-angle distributions of trapped particles and with particle streaming along magnetic field lines inside and outside the trapping region of the dark magnetosphere. Efforts should be made to determine the energy dependence of these observations and to extend such measurements to lower energies. In view of our findings, future investigation along these lines must involve a substantial number of low-latitude traversals of the region near the midnight meridian between about 6 and 13 Re. Thus, the suitability of satellites having either very long periods or nearly circular orbits is doubtful.

A detector primarily designed to furnish such data must naturally have a much greater time resolution; this is certainly within the capabilities of the scintillation counter. Other possible improvements may include somewhat better directionality, a thinner cover, a lower electronic threshold, and an increased accumulator capacity. It appears to us that the high sensitivity should be preserved at the expense of useful information inside the high-flux regions of the radiation zones.

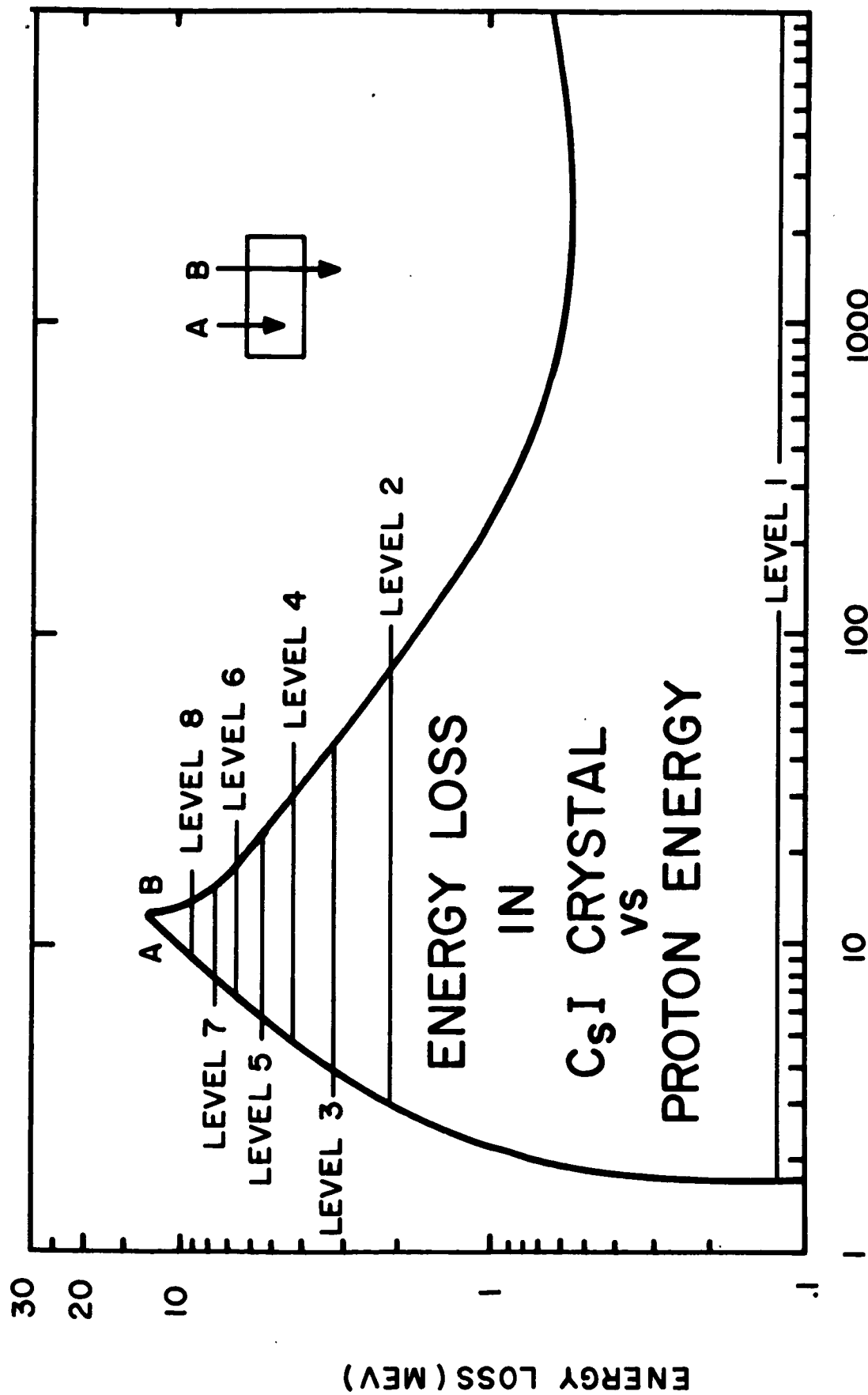


MAGNETIC EQUATORIAL PLANE

FIG. I  
THE REGION COVERED BY EXPLORERS XII AND XIV



**FIG. 2**  
**DETECTOR ARRANGEMENT IN THE PAYLOAD**



PROTON KINETIC ENERGY (MEV)

FIG. 3

SINGLE CRYSTAL RESPONSE TO PROTONS

# SCINTILLATION COUNTER FIRST LEVEL CALIBRATION

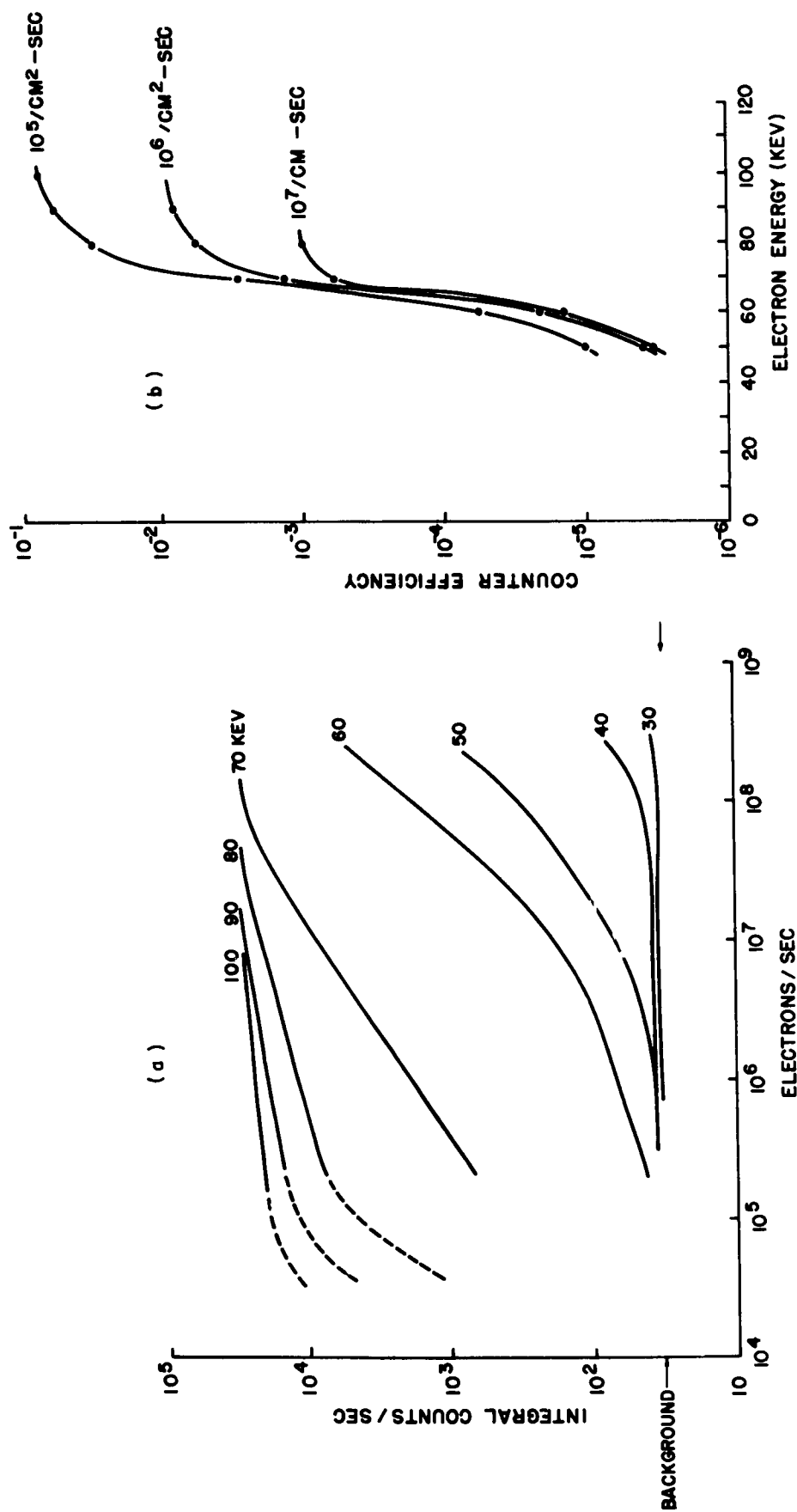


FIG. 4

SINGLE CRYSTAL RESPONSE TO LOW ENERGY ELECTRONS

# GEIGER COUNTER

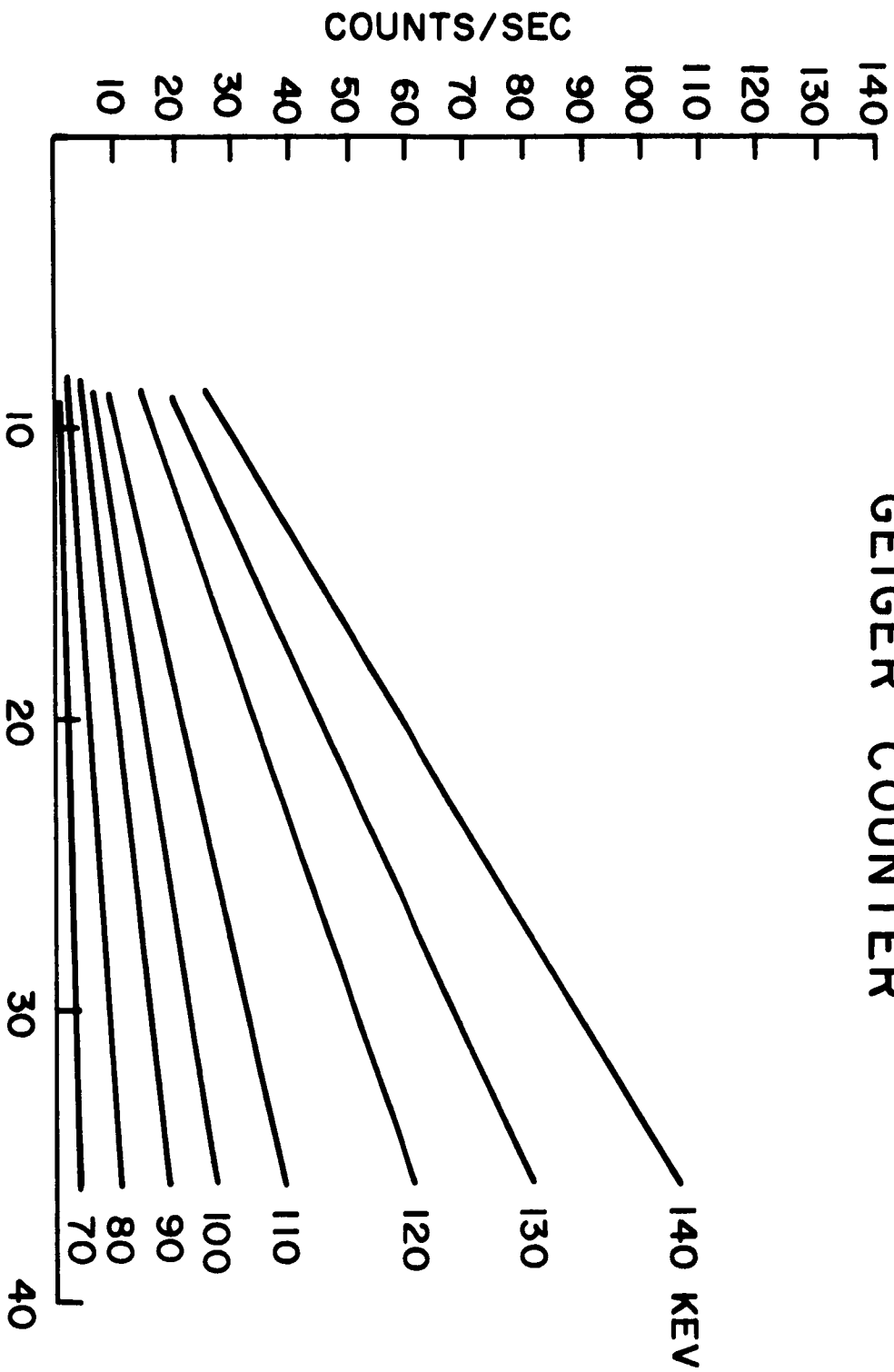


FIG. 5  
ELECTRONS/SEC ( $\times 10^7$ )

GEIGER COUNTER RESPONSE TO LOW ENERGY ELECTRONS

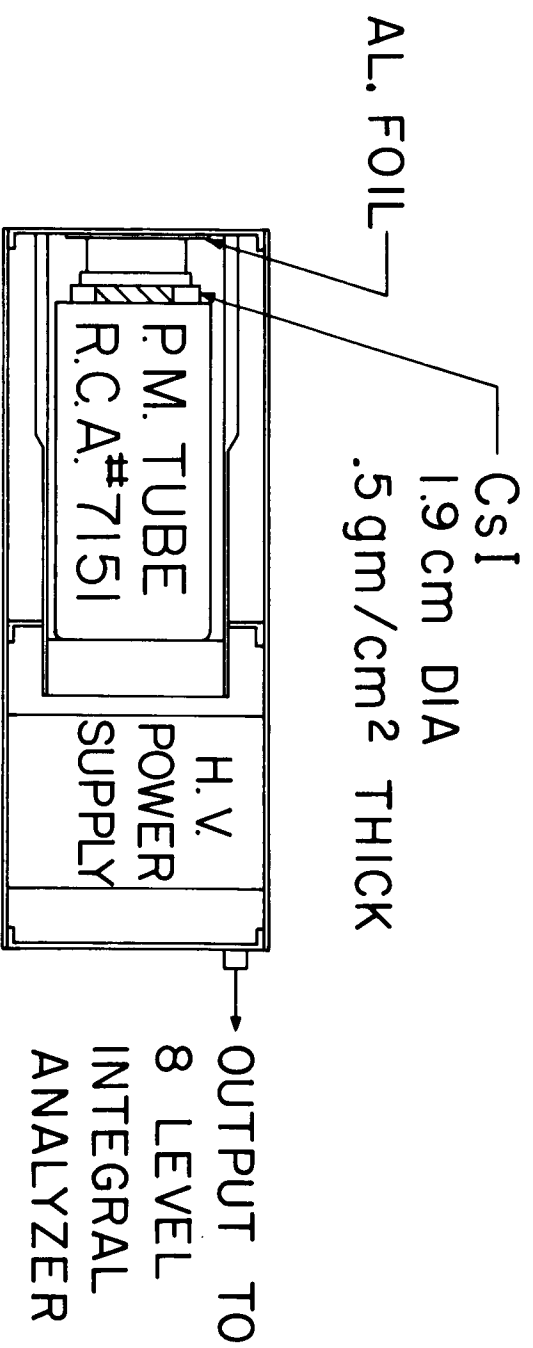
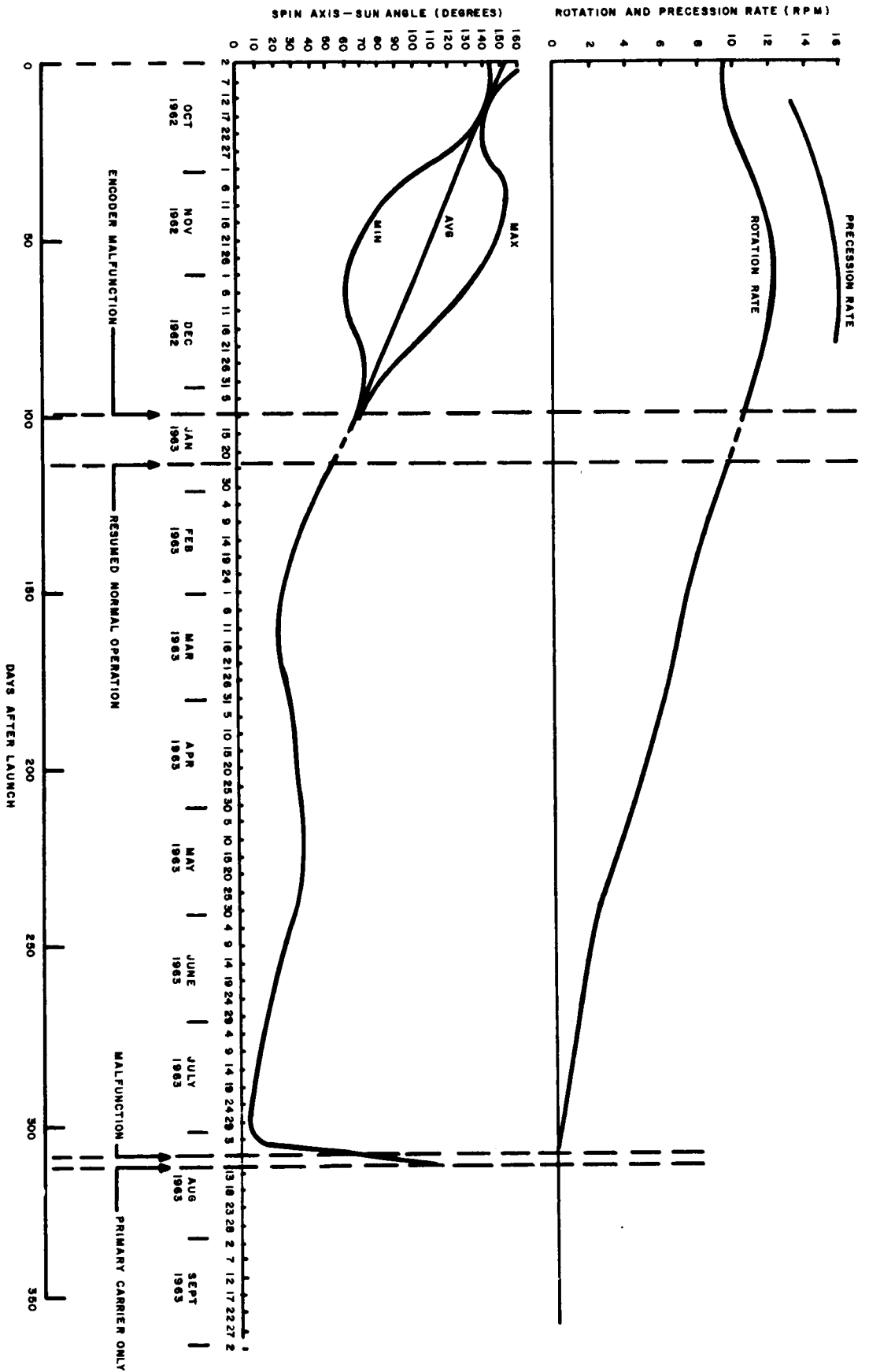
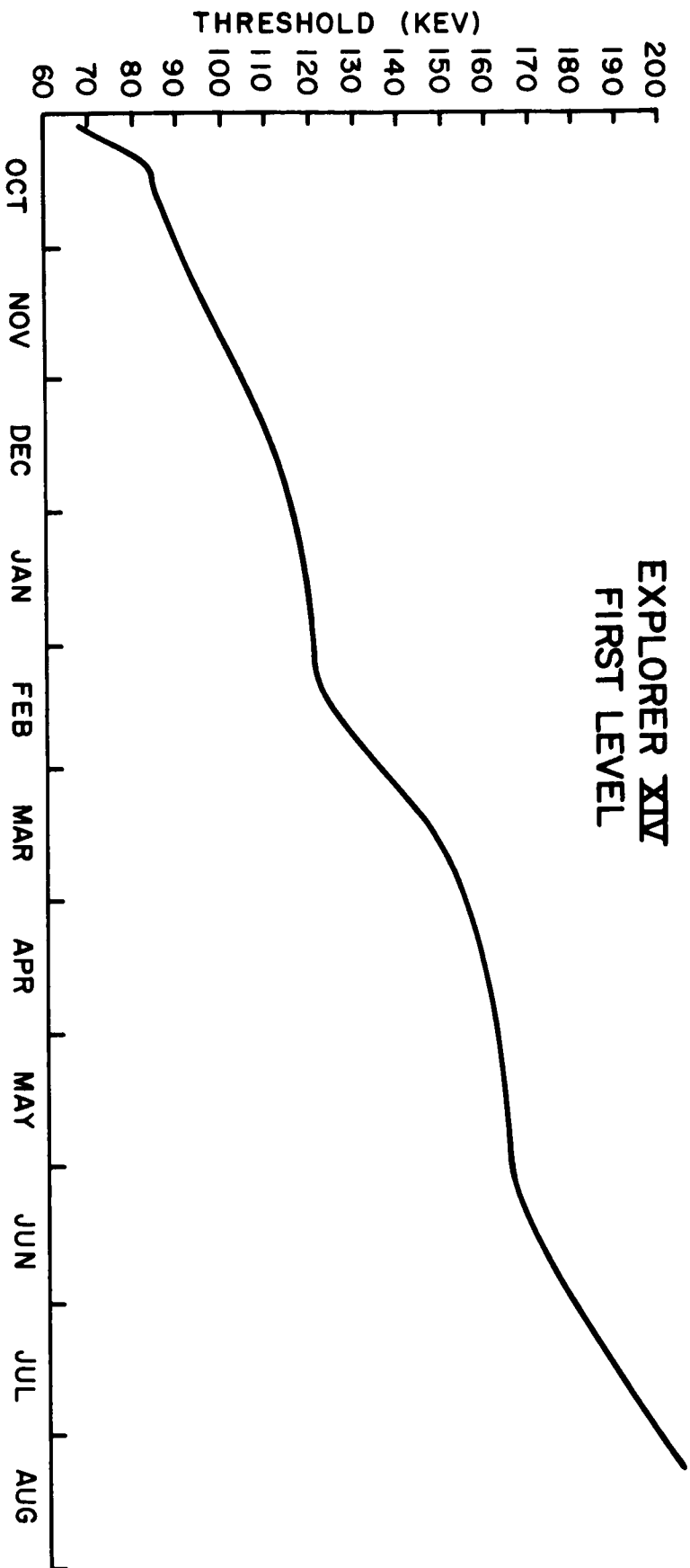


FIG. 6  
SCINTILLATION COUNTER

**FIG. 7**  
**EXPLORER XIV SPIN RATE AND**  
**SPIN AXIS SUN ANGLE**





**FIG. 8**  
**SINGLE CRYSTAL FLIGHT CALIBRATION**

**EXPLORER XIV**

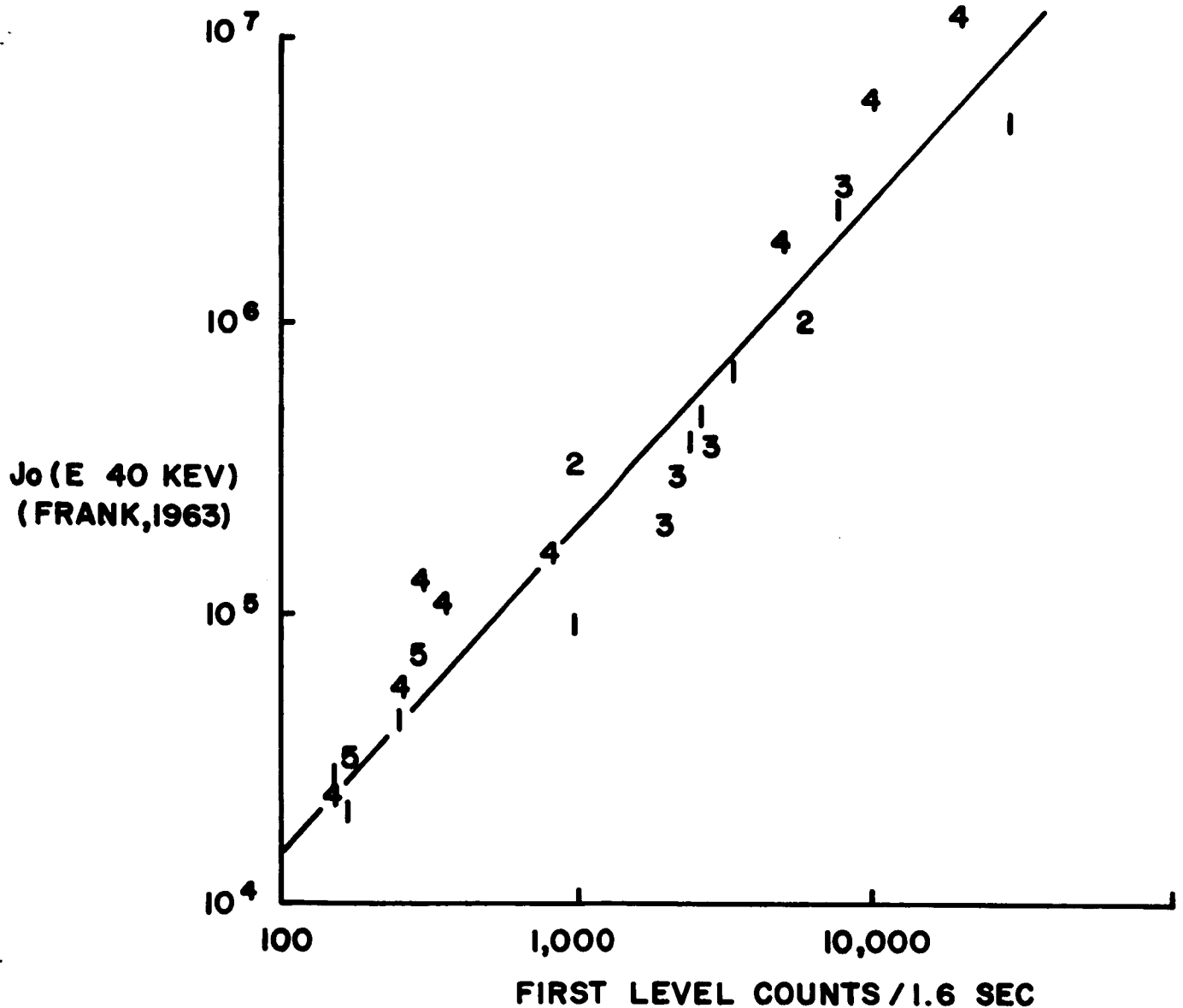
**1.OCT. 24, 1962 —OUT**

**2.DEC. 16, 1962 —OUT**

**3.DEC. 23, 1962 —IN**

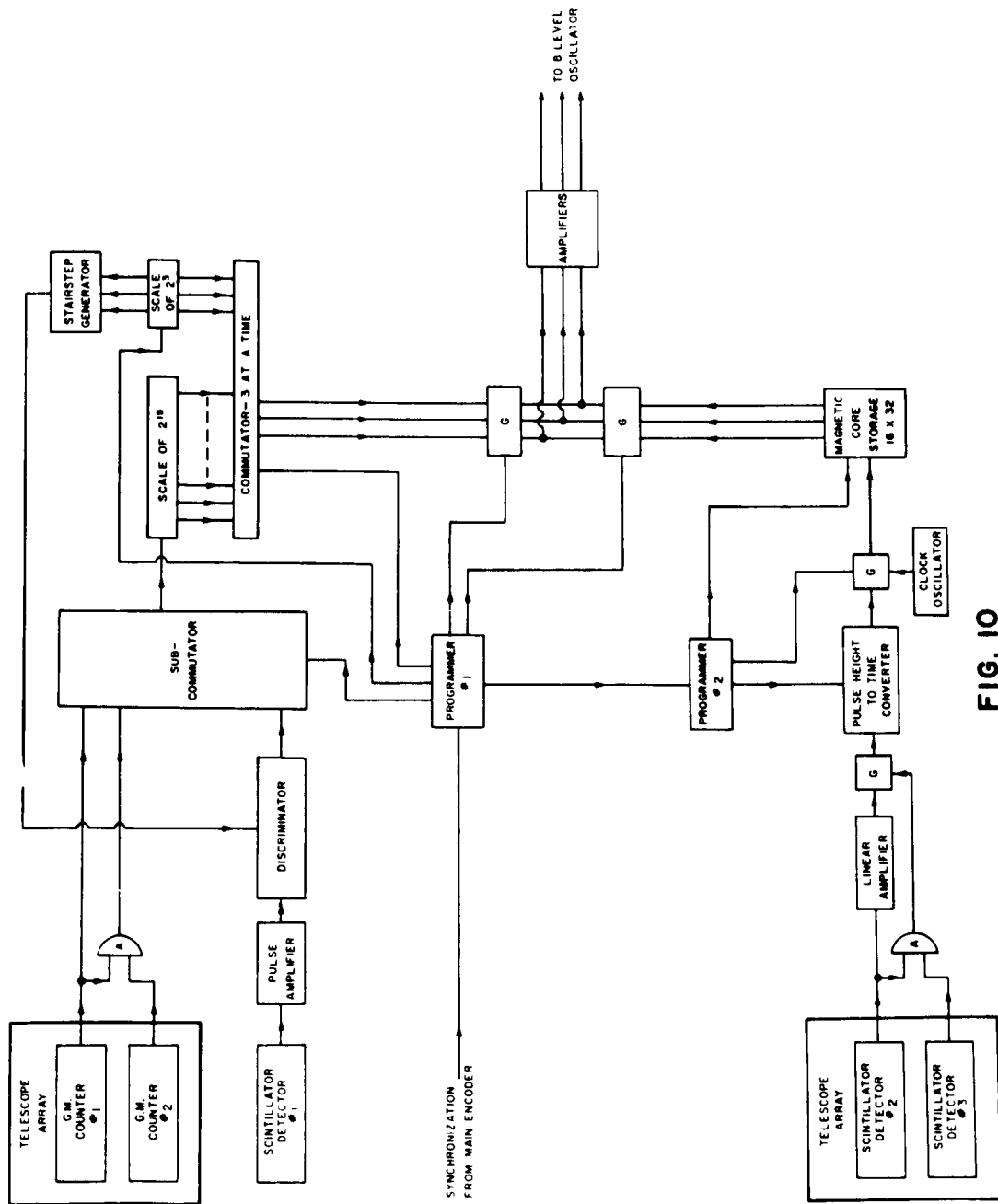
**4.APR. 5, 1963 —IN**

**5.JUL. 10, 1963 —OUT**



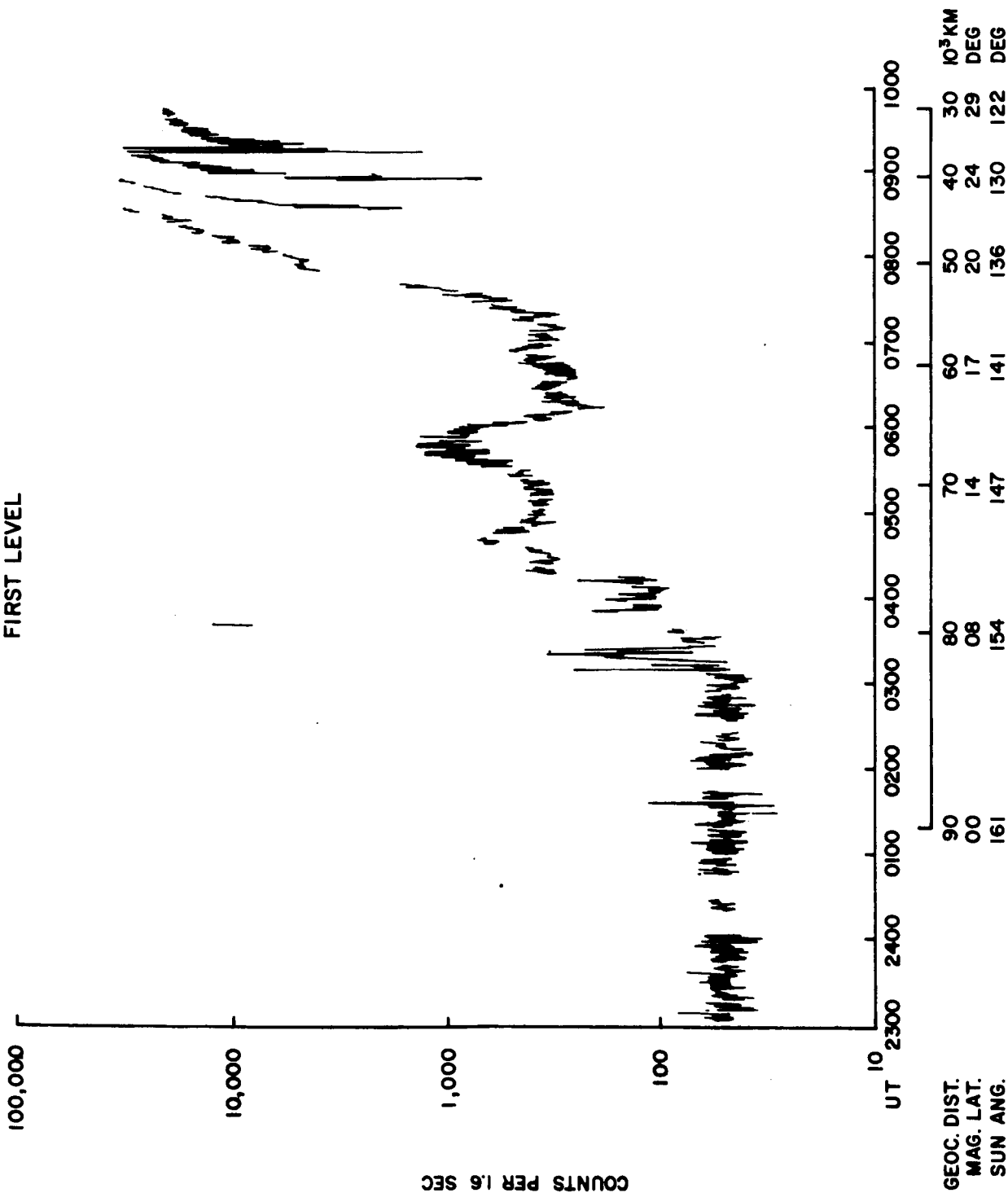
**FIG. 9**

**FIRST LEVEL IN-FLIGHT RESPONSE VS.  
MEASURED ELECTRON FLUXES IN MAGNETOSPHERE**



**FIG. 10**  
**BLOCK DIAGRAM OF ELECTRONIC INSTRUMENTATION**

# EXPLORER XIV FIRST LEVEL

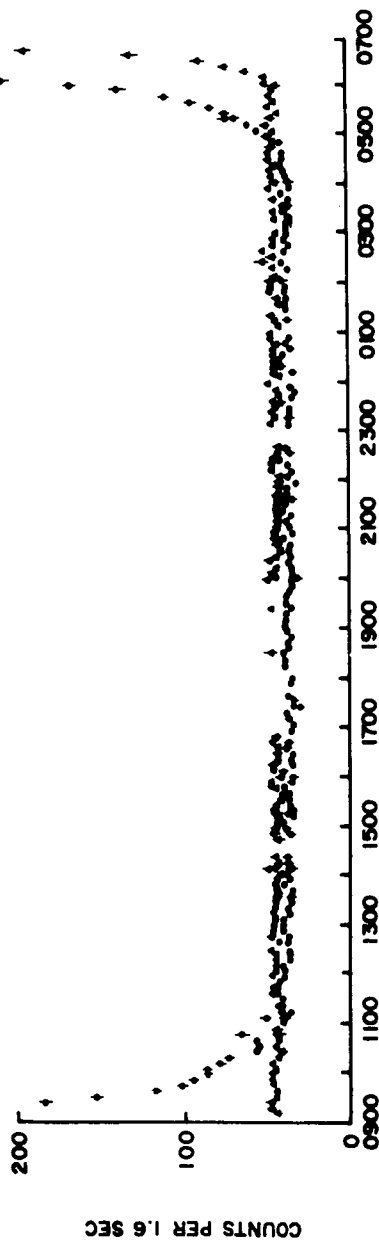


3 JANUARY 1963

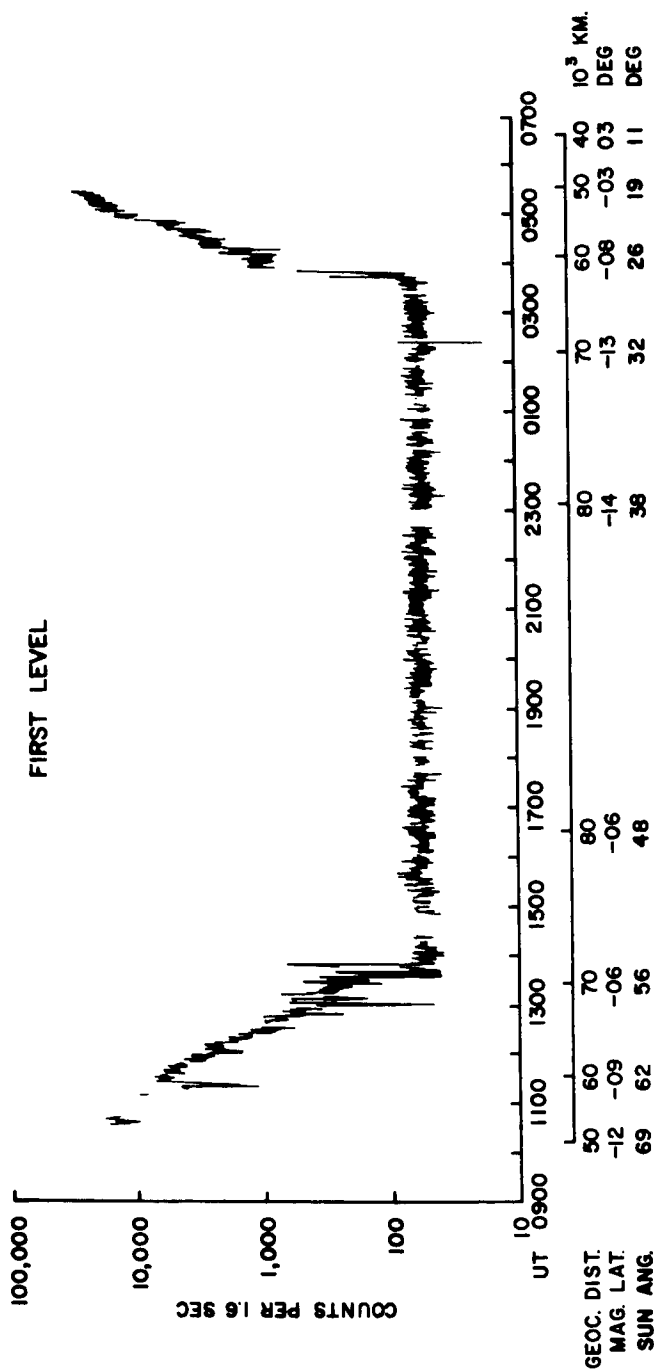
FIG. II

INBOUND PASS OF JAN. 3, 1963

EXPLORER XII  
 ↓ SECOND LEVEL  
 ↓ GEIGER COUNTER



FIRST LEVEL



8-9 OCTOBER 1961

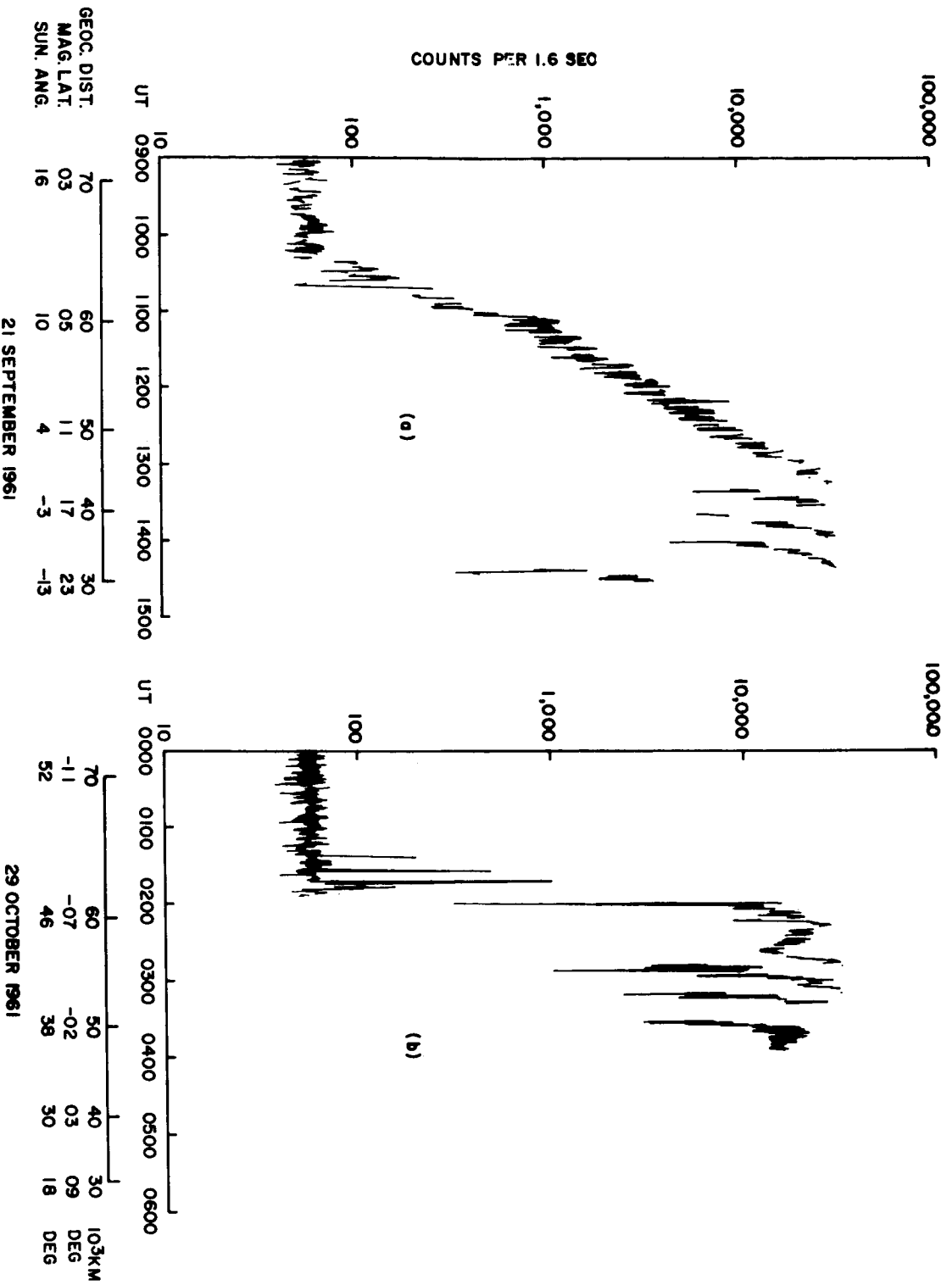
FIG. 12

SUCCESSIVE BOUNDARY CROSSINGS DURING ORBIT OF OCT. 8-9, 1963

GEOC. DIST.  
 MAG. LAT.  
 SUN ANG.

50	60	70	80	80	70	60	50	40	10 <sup>3</sup> KM.
-12	-09	-06	-06	-06	-13	-08	-03	03	DEG
69	62	56	36	36	32	26	19	11	DEG

EXPLORER XII  
FIRST LEVEL



# PARTICLE BOUNDARY

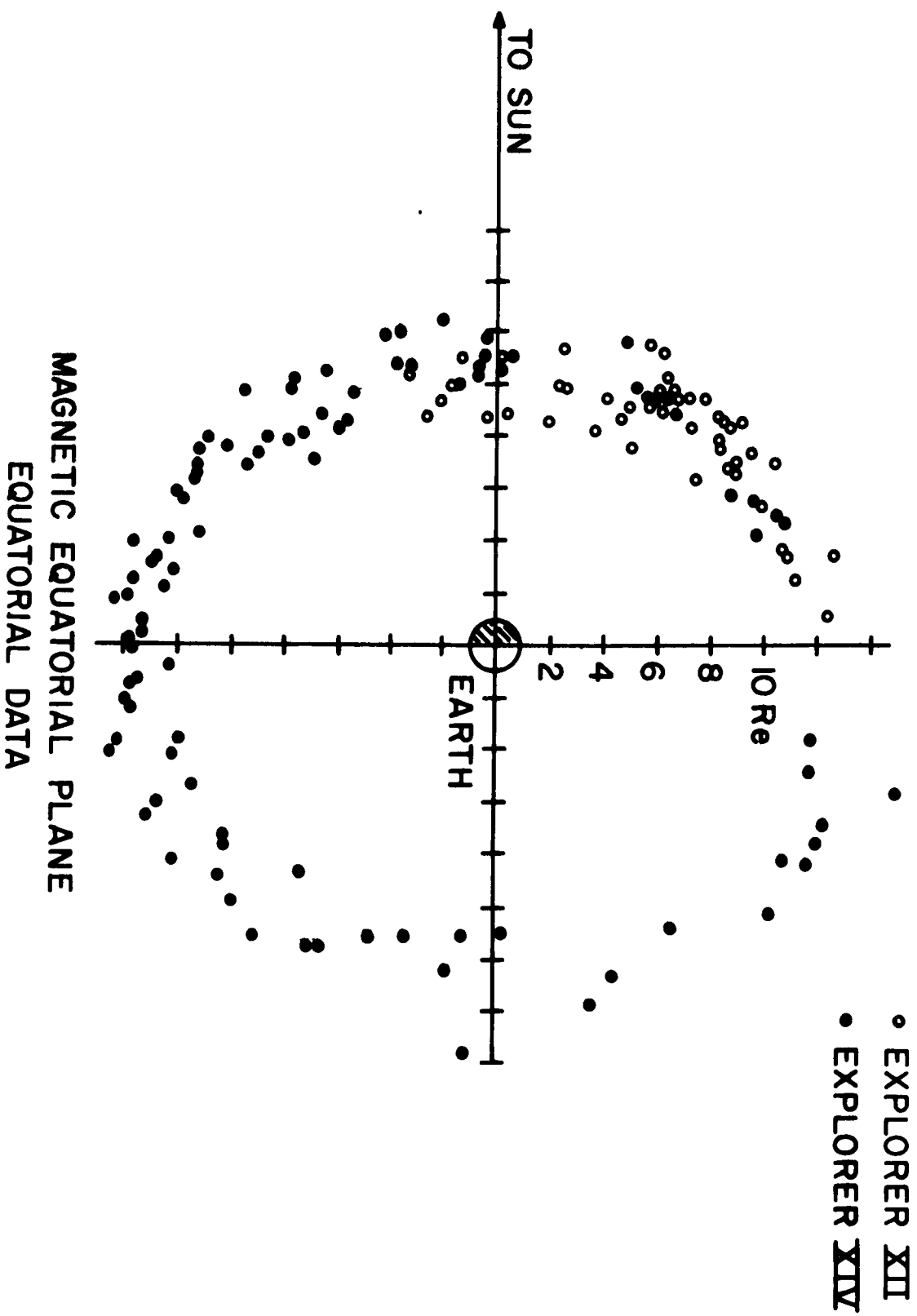
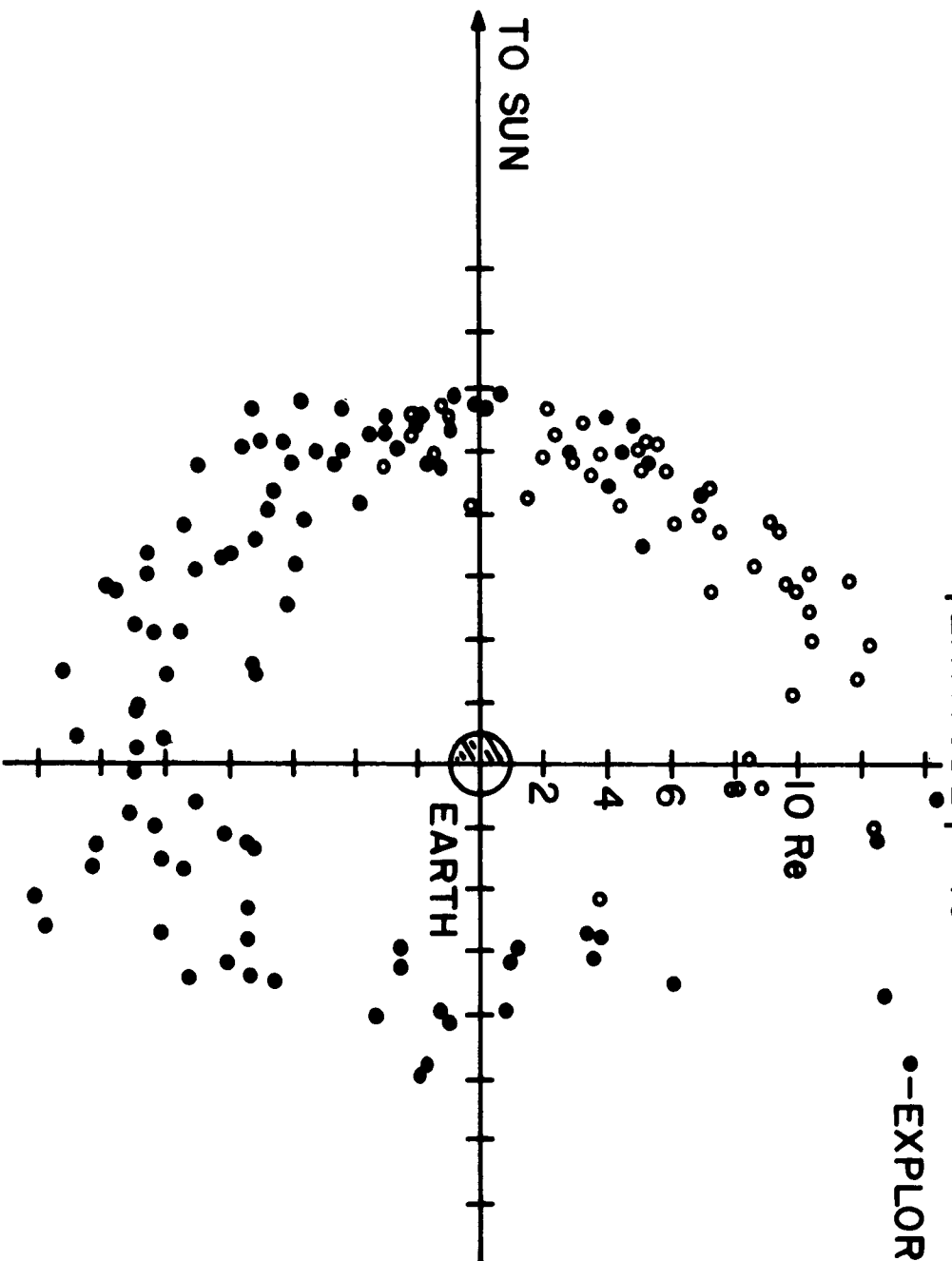


FIG. 14

# PARTICLE BOUNDARY

$|\text{LATITUDE}| > 10^\circ$

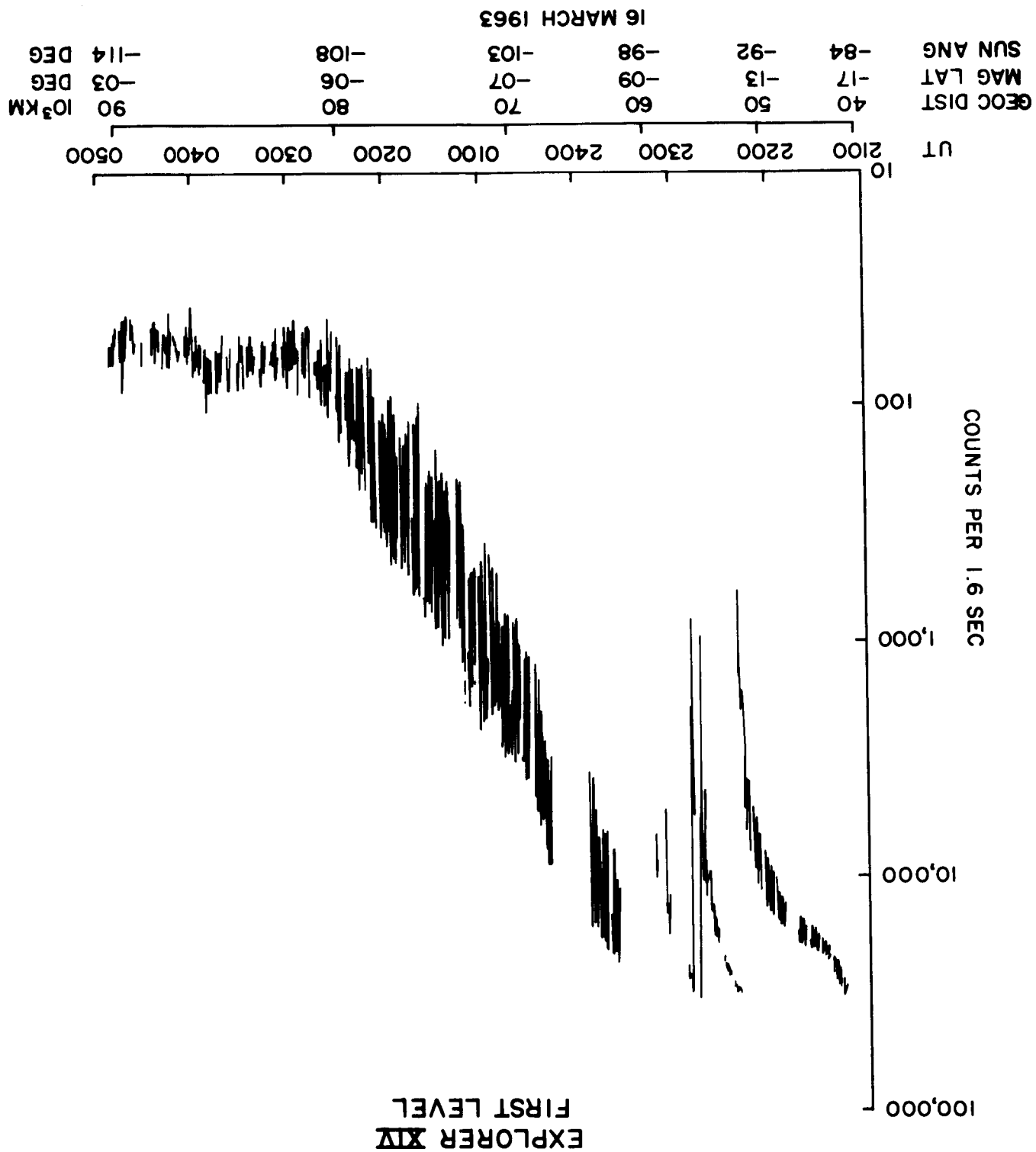
○--EXPLORER XII  
●--EXPLORER XIV



MAGNETIC EQUATORIAL PLANE

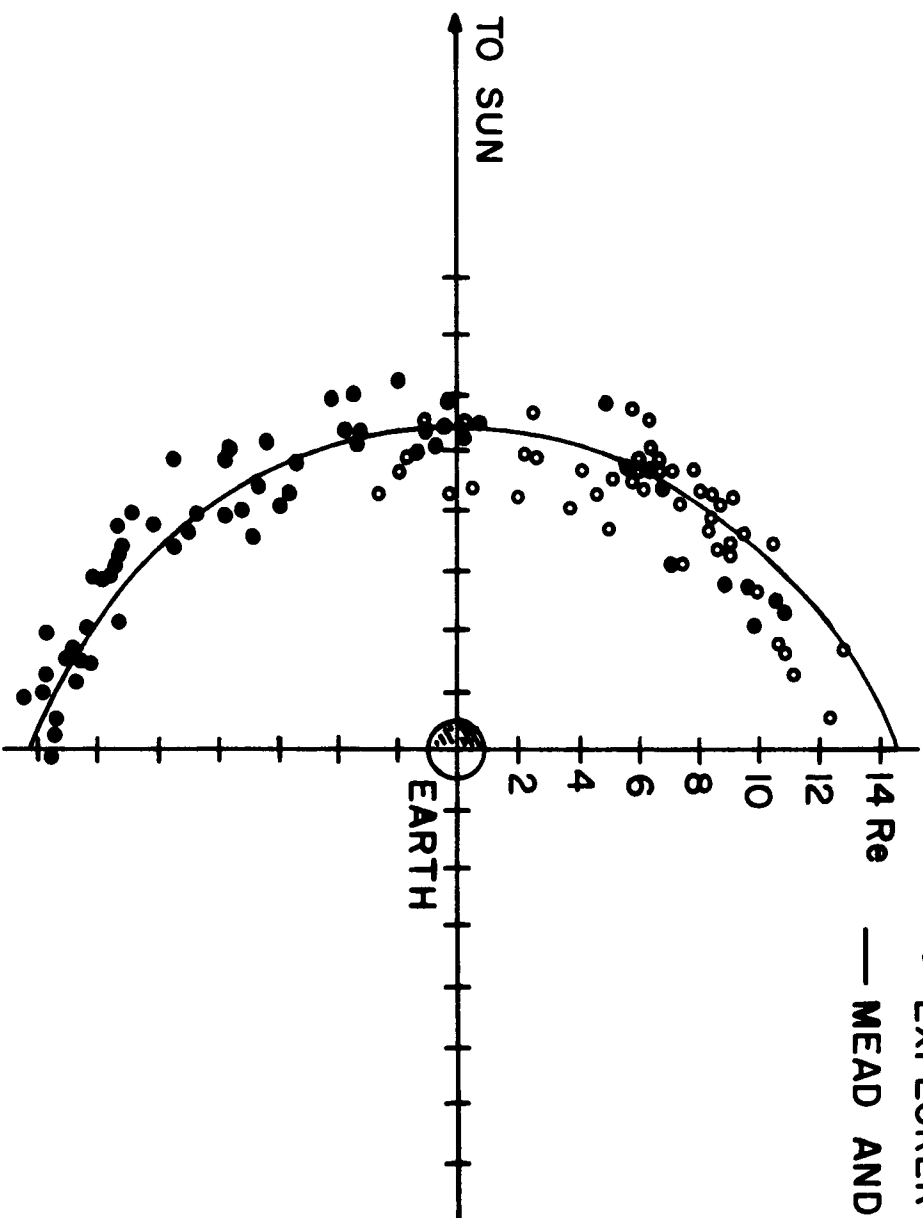
FIG. 15

FIG. 16  
OUTBOUND PASS OF MAR. 16, 1963



# PARTICLE BOUNDARY

- EXPLORER XII
- EXPLORER XIV
- MEAD AND BEARD (1963)



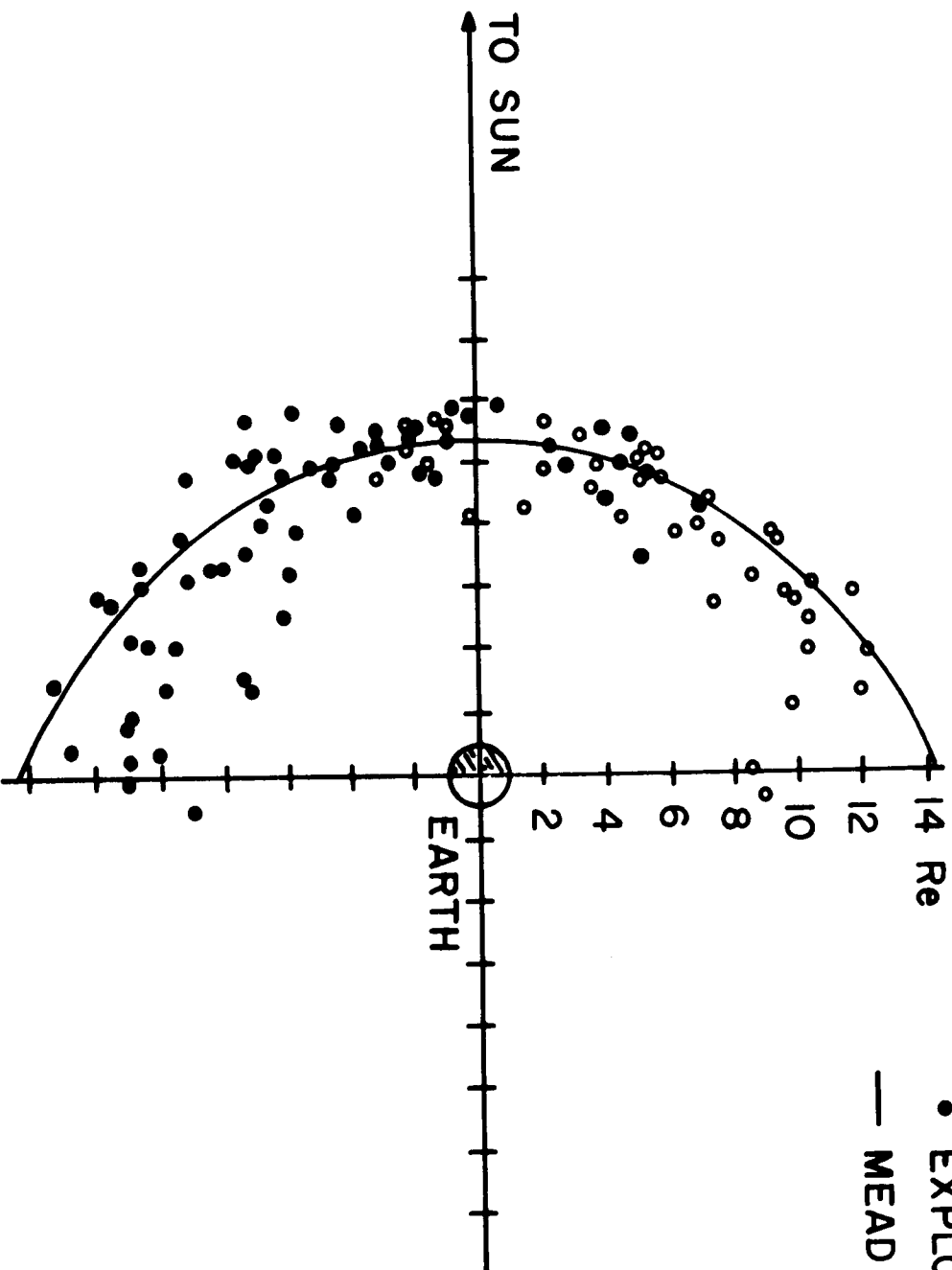
# PARTICLE BOUNDARY

$|\text{LATITUDE}| > 10^\circ$

• EXPLORER XII

• EXPLORER XIV

— MEAD AND BEARD (1963)



MAGNETIC EQUATORIAL PLANE

FIG. 18

FIT TO THEORETICAL MAGNETOPAUSE

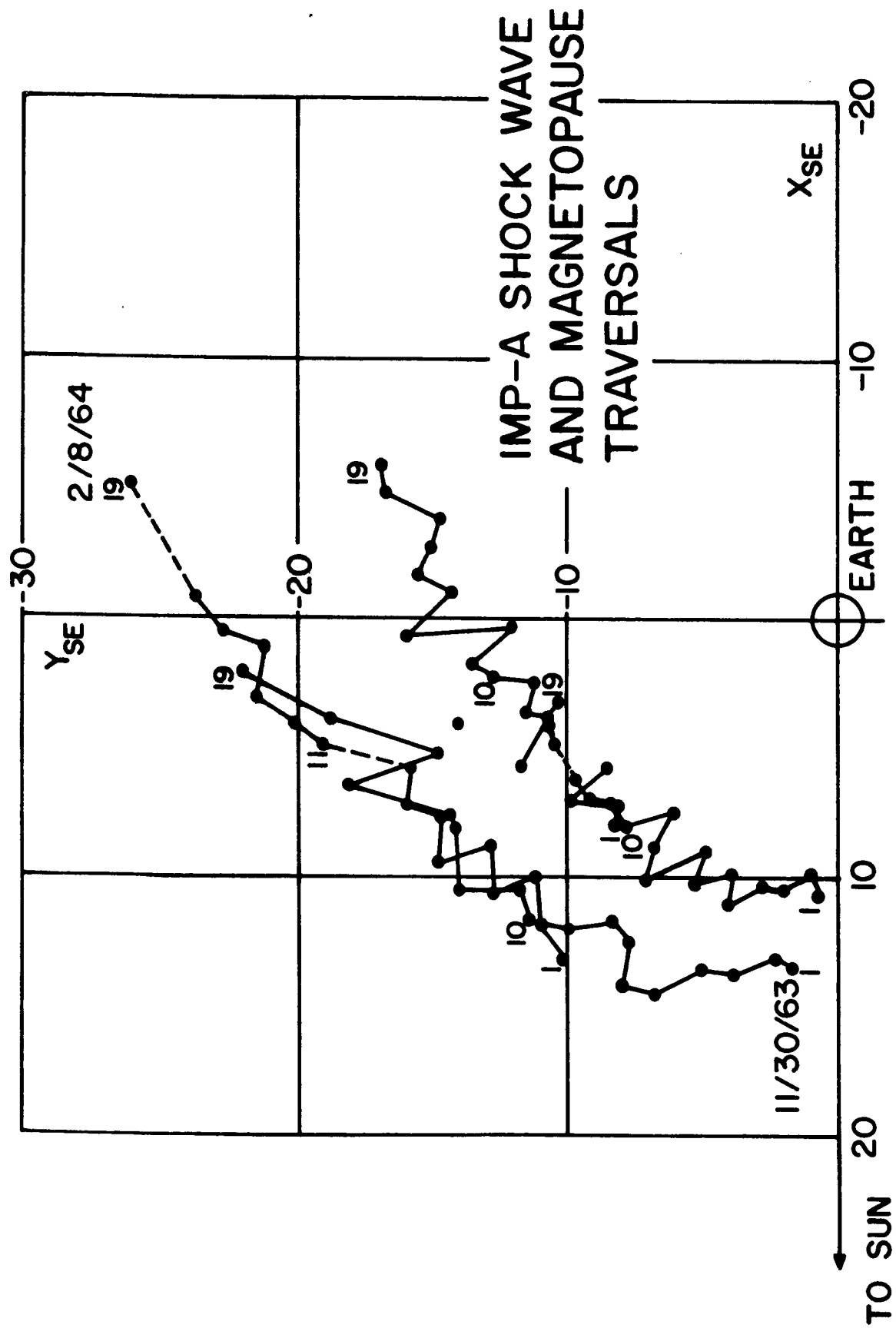
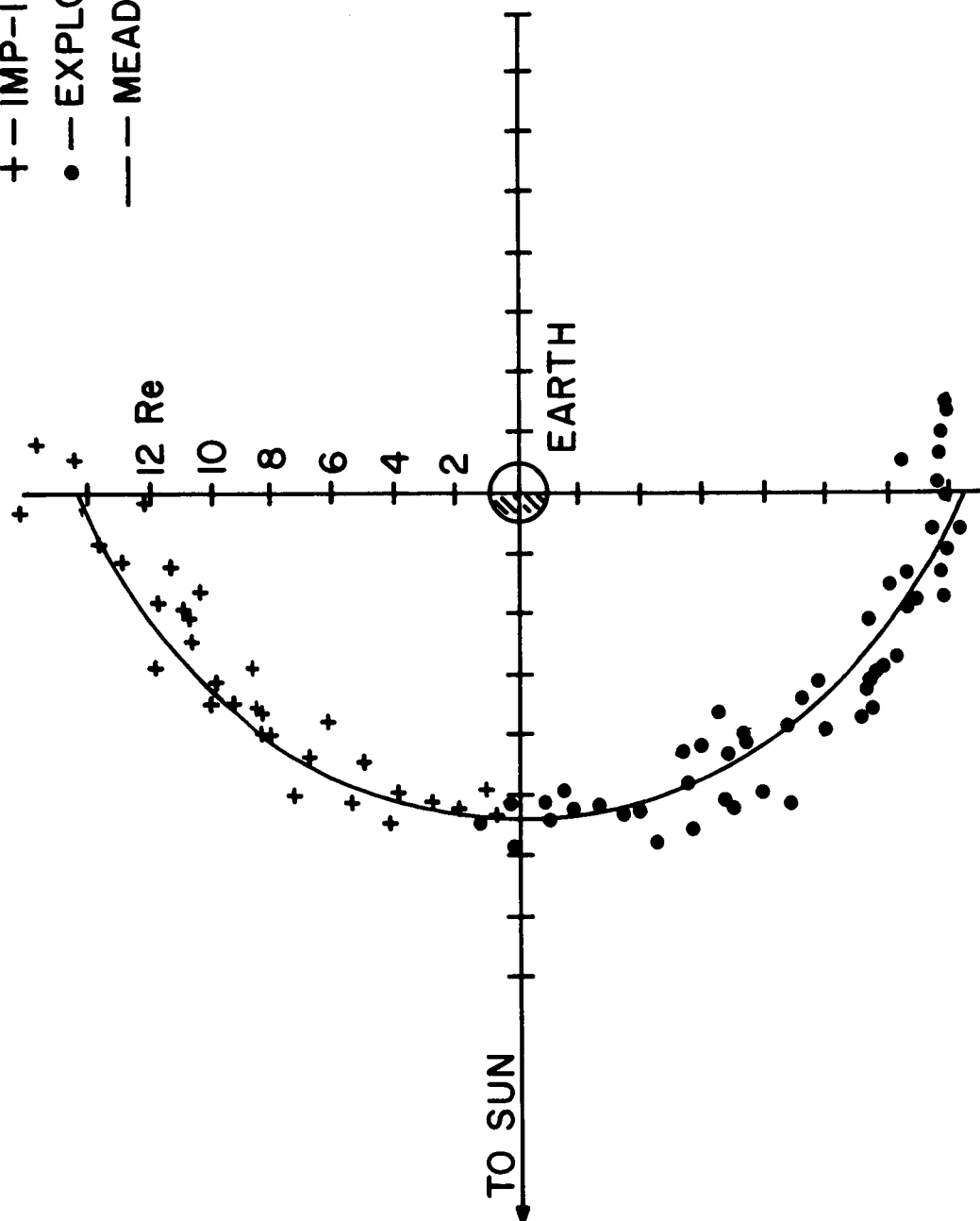


FIG. 19

- + — IMP-1 MAGNETIC FIELD EXP.
- — EXPLORER XIV
- — MEAD AND BEARD (1963)

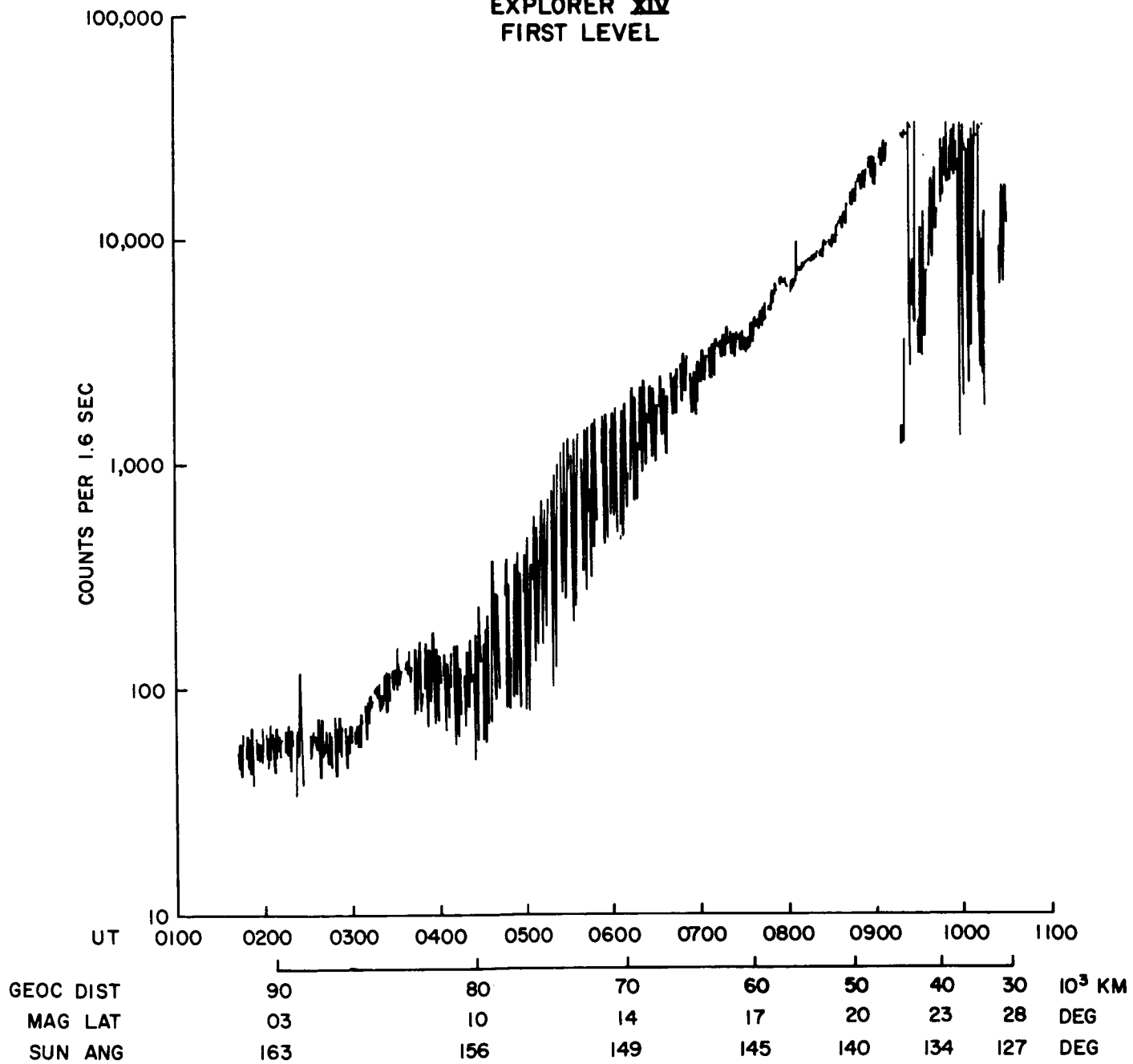


ECLIPTIC PLANE

FIG. 20

THE BOUNDARY OF THE MAGNETOSPHERE FROM  
MAGNETIC FIELD AND TRAPPED ELECTRON DATA

EXPLORER XIV  
FIRST LEVEL

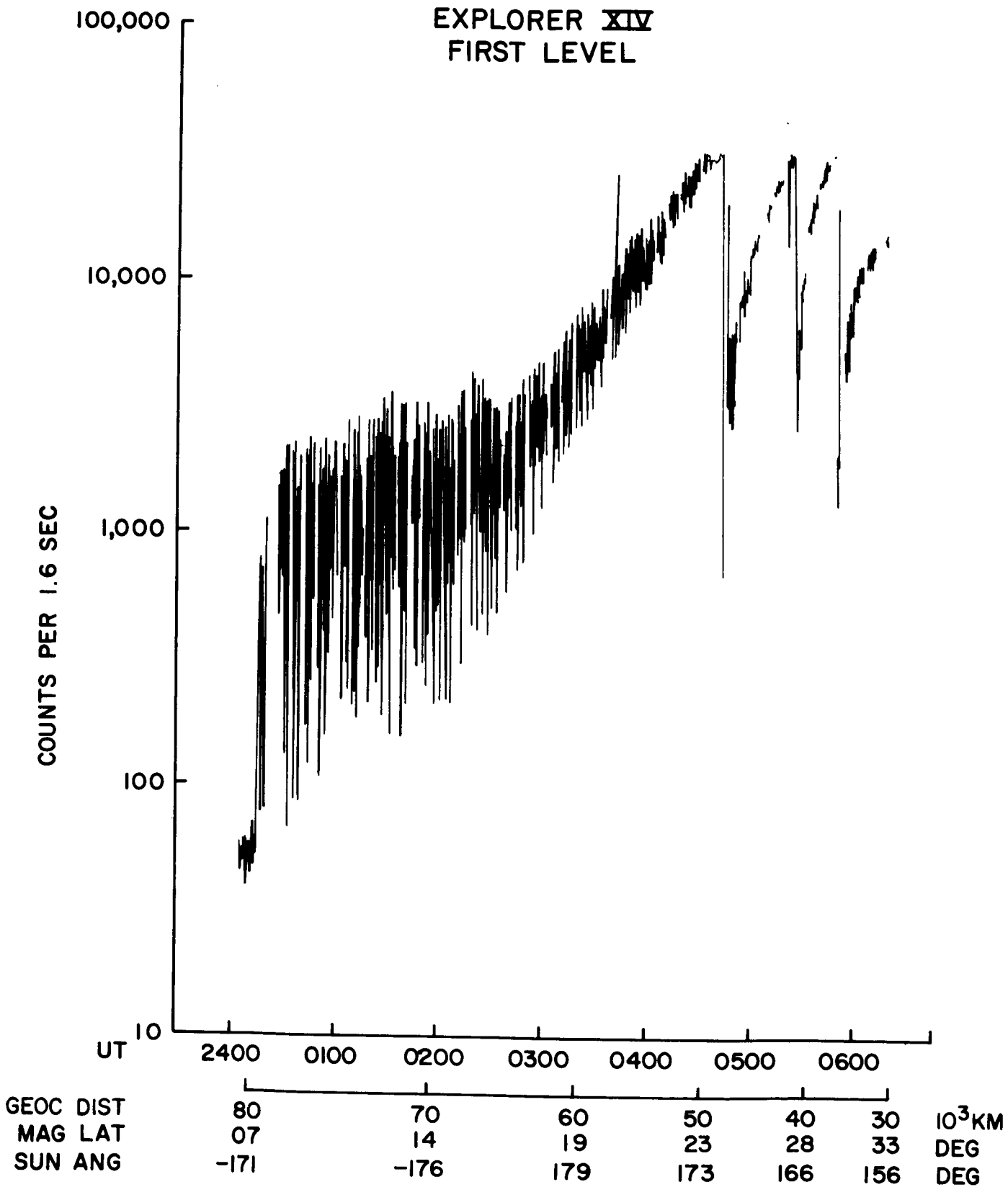


6 JANUARY 1963

FIG. 21

INBOUND PASS OF JAN. 6, 1963

# EXPLORER XIV FIRST LEVEL



4 FEBRUARY 1963  
FIG. 22  
INBOUND PASS OF FEB. 4, 1963

EXPLORER XIV  
FEB. 4, 1963  
0036 UT

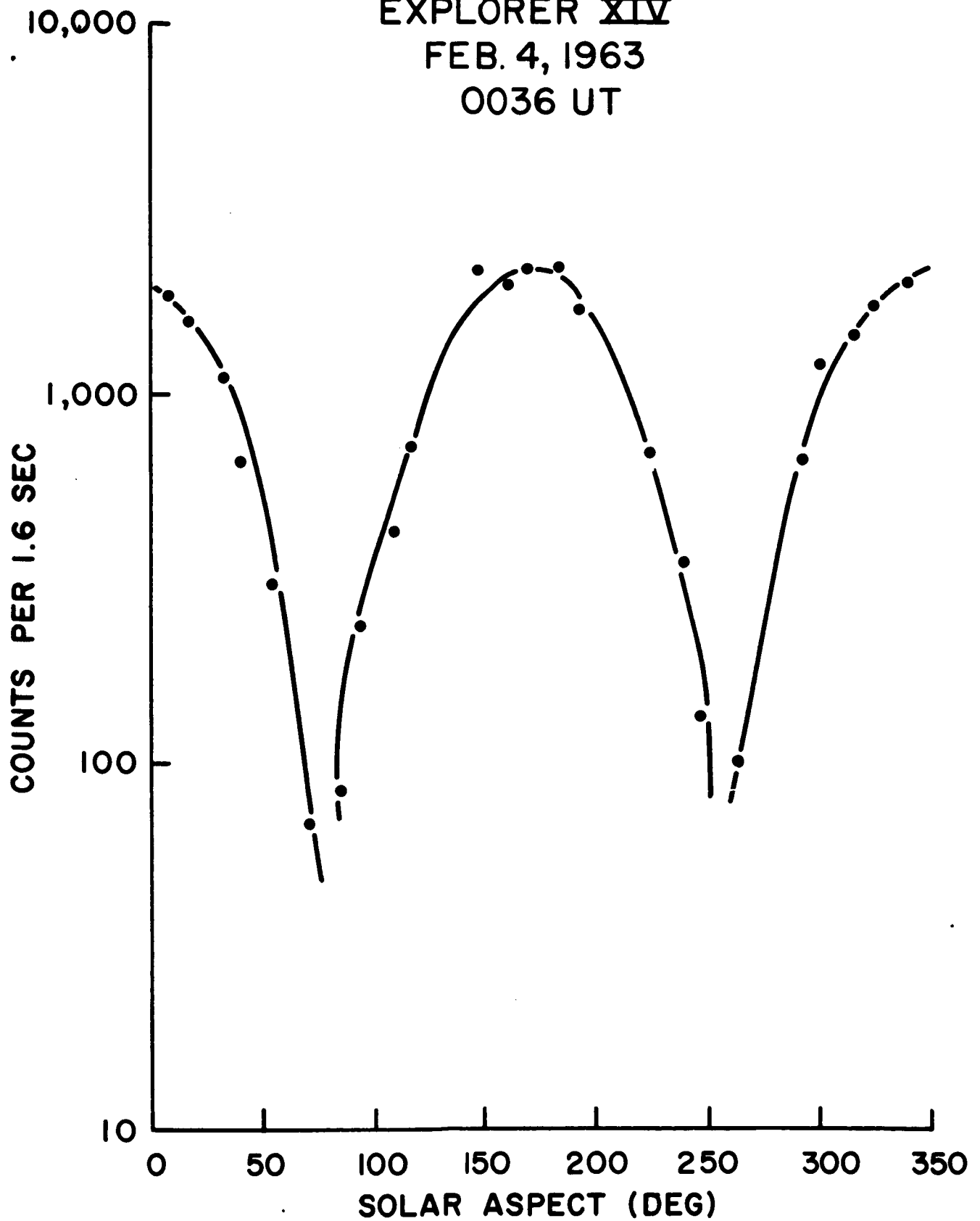
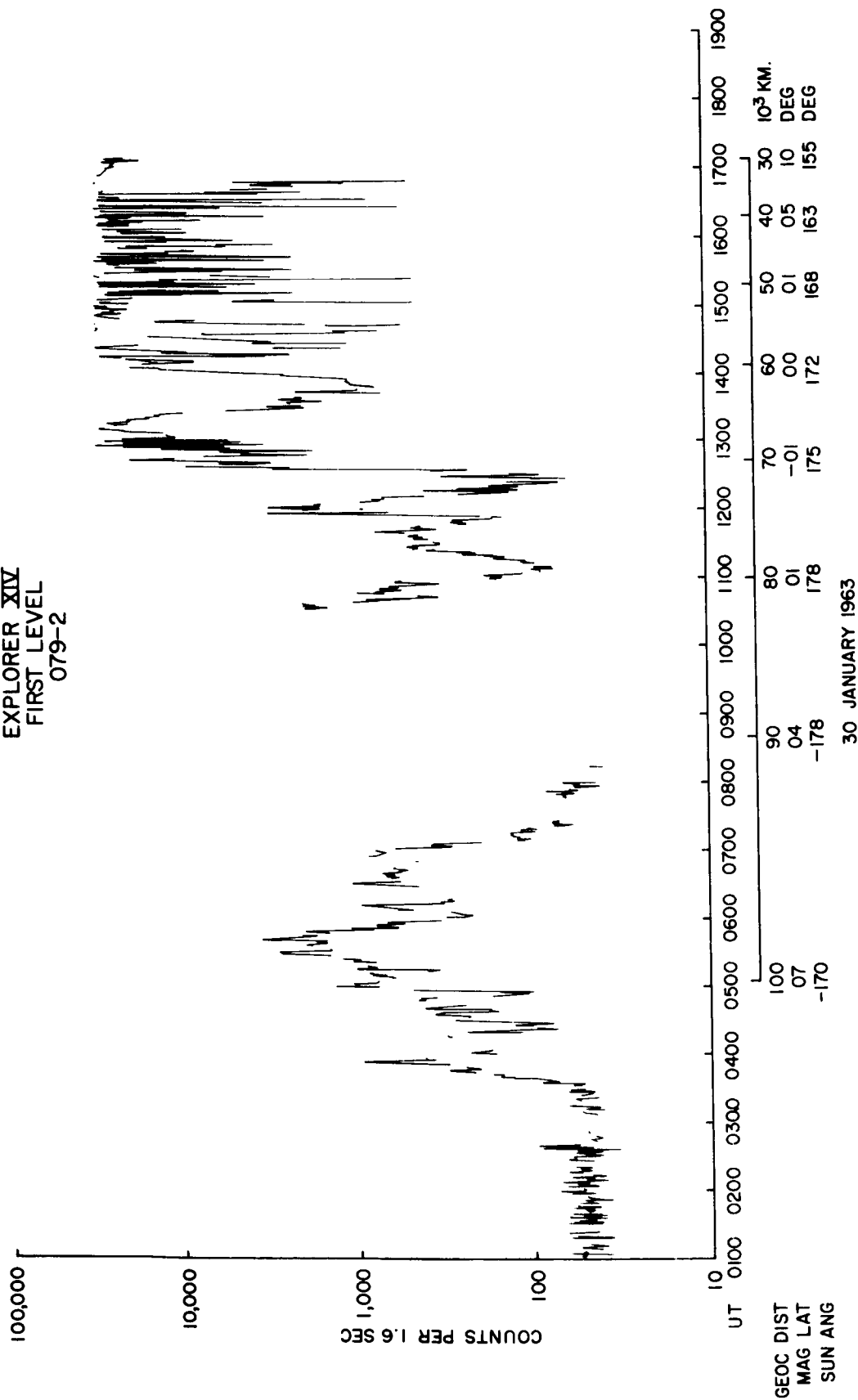


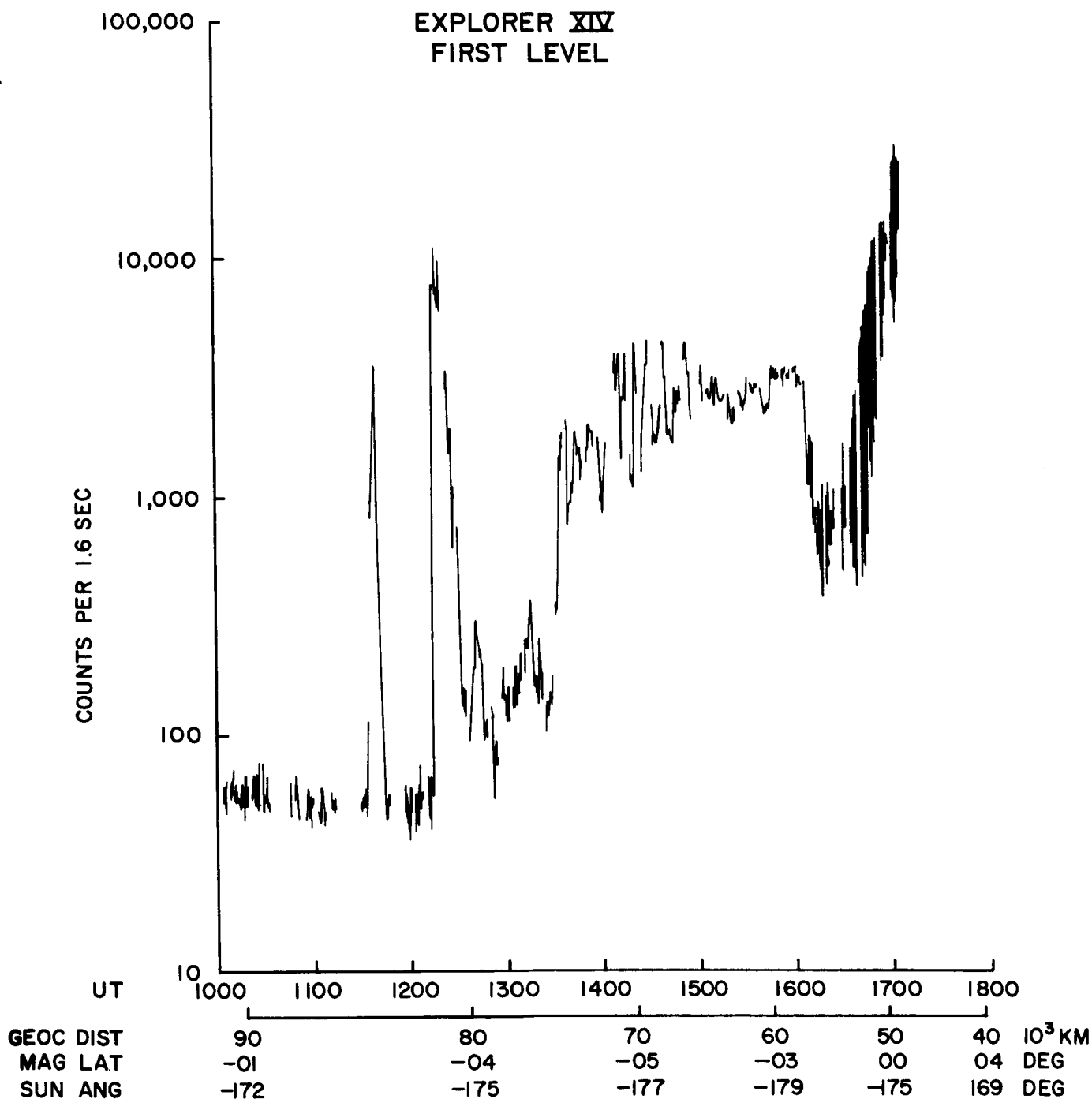
FIG. 23  
COUNTING RATE VS. SOLAR ASPECT ANGLE

EXPLORER XIV  
FIRST LEVEL  
079-2



**FIG. 24**  
**INBOUND PASS OF JAN 30, 1963**

# EXPLORER XIV FIRST LEVEL

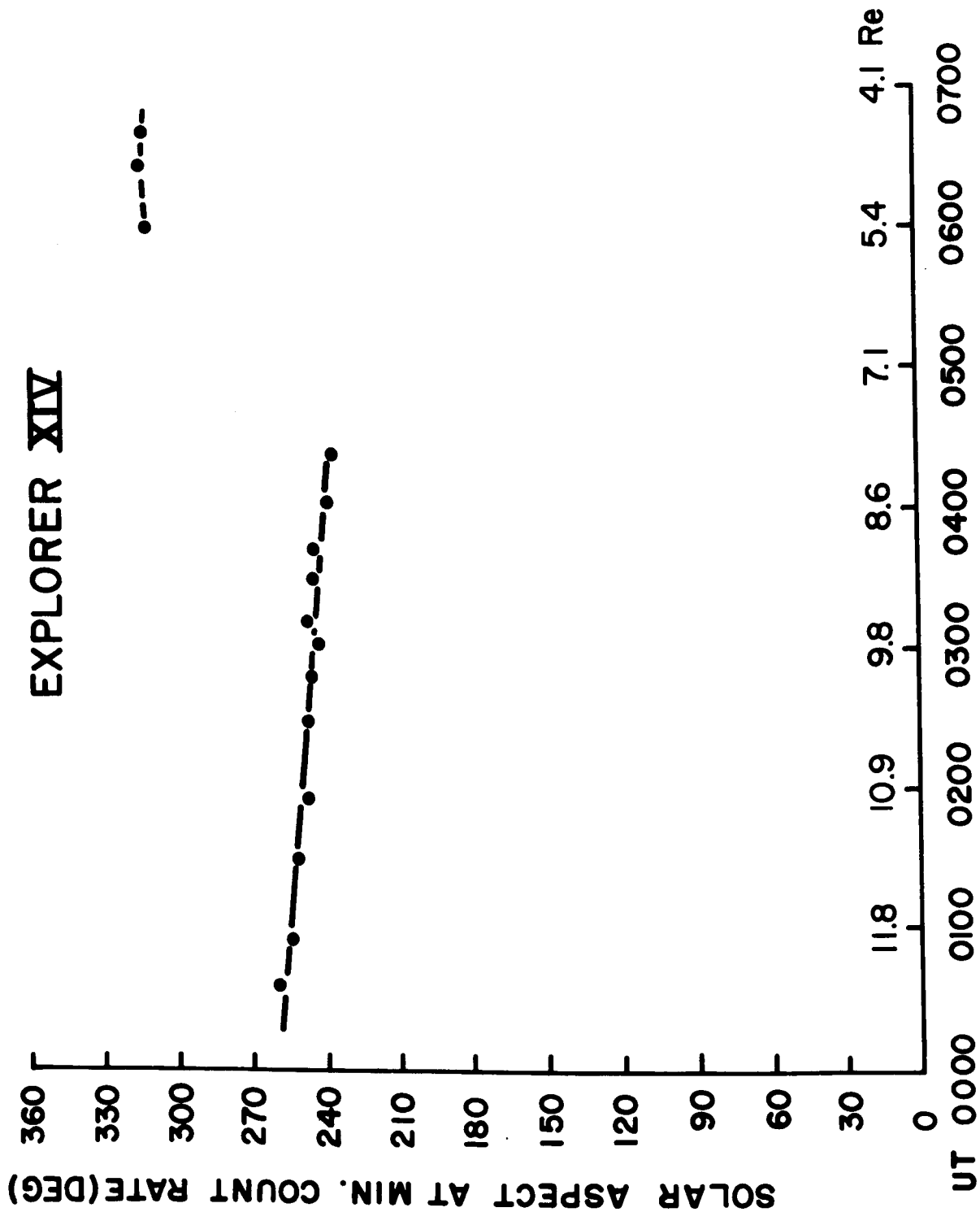


5 FEBRUARY 1963

FIG. 25

INBOUND PASS OF FEB. 5, 1963

# EXPLORER XIV



FEB. 4, 1963

FIG. 26

ANISOTROPIC FEATURES OF TRAPPED ELECTRONS

# EXPLORER XIV

FEB. 4, 1963

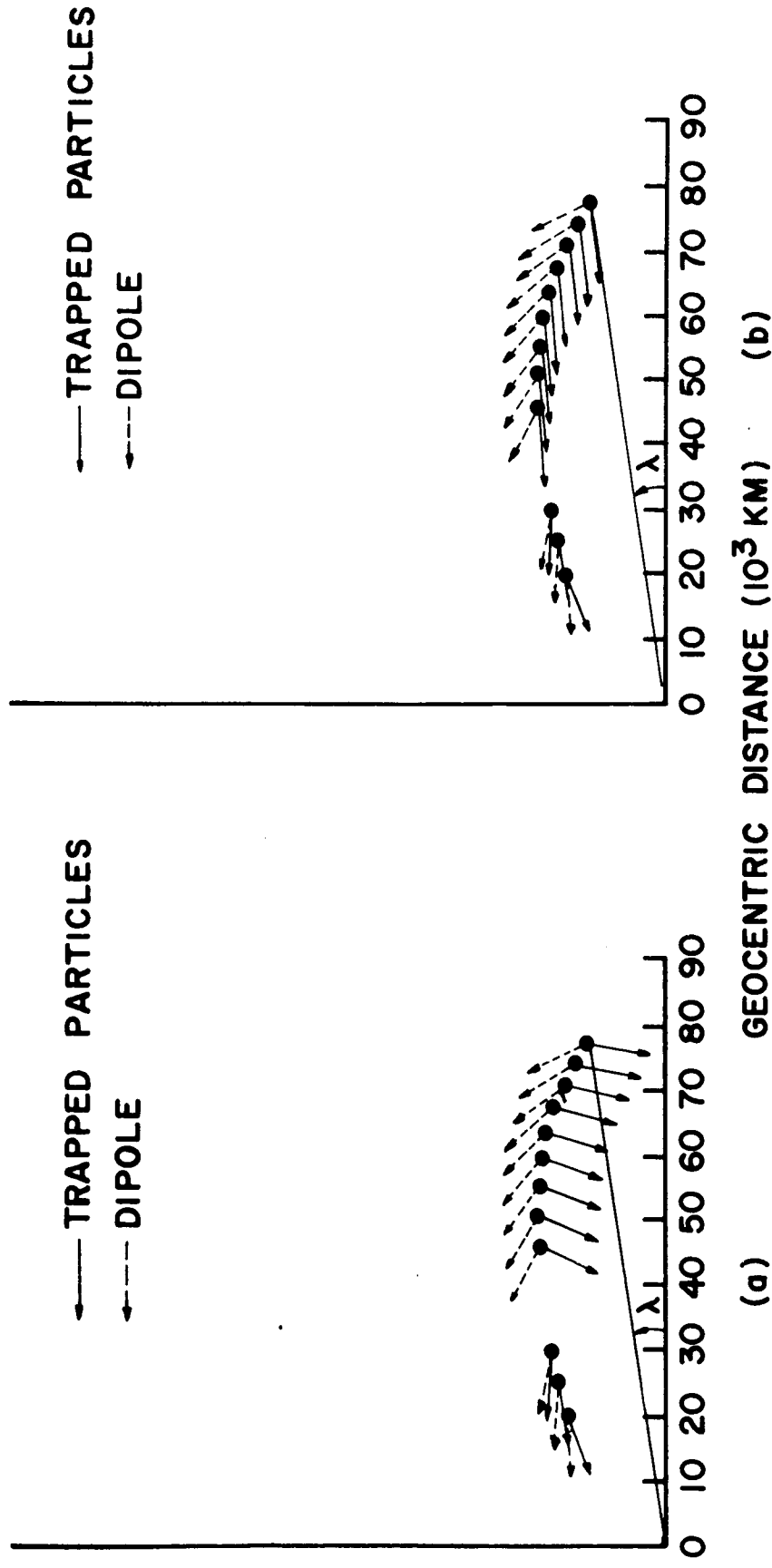
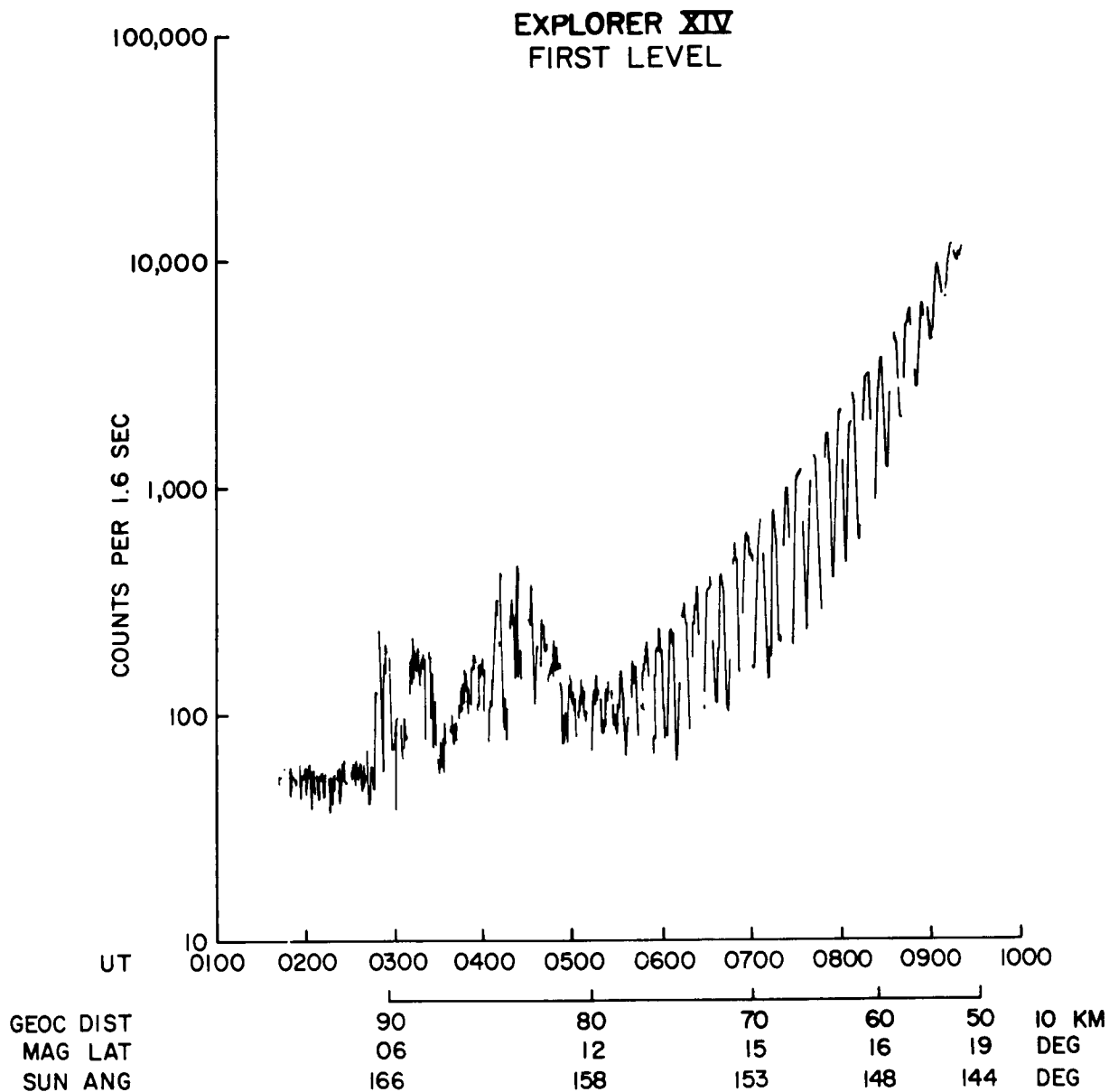


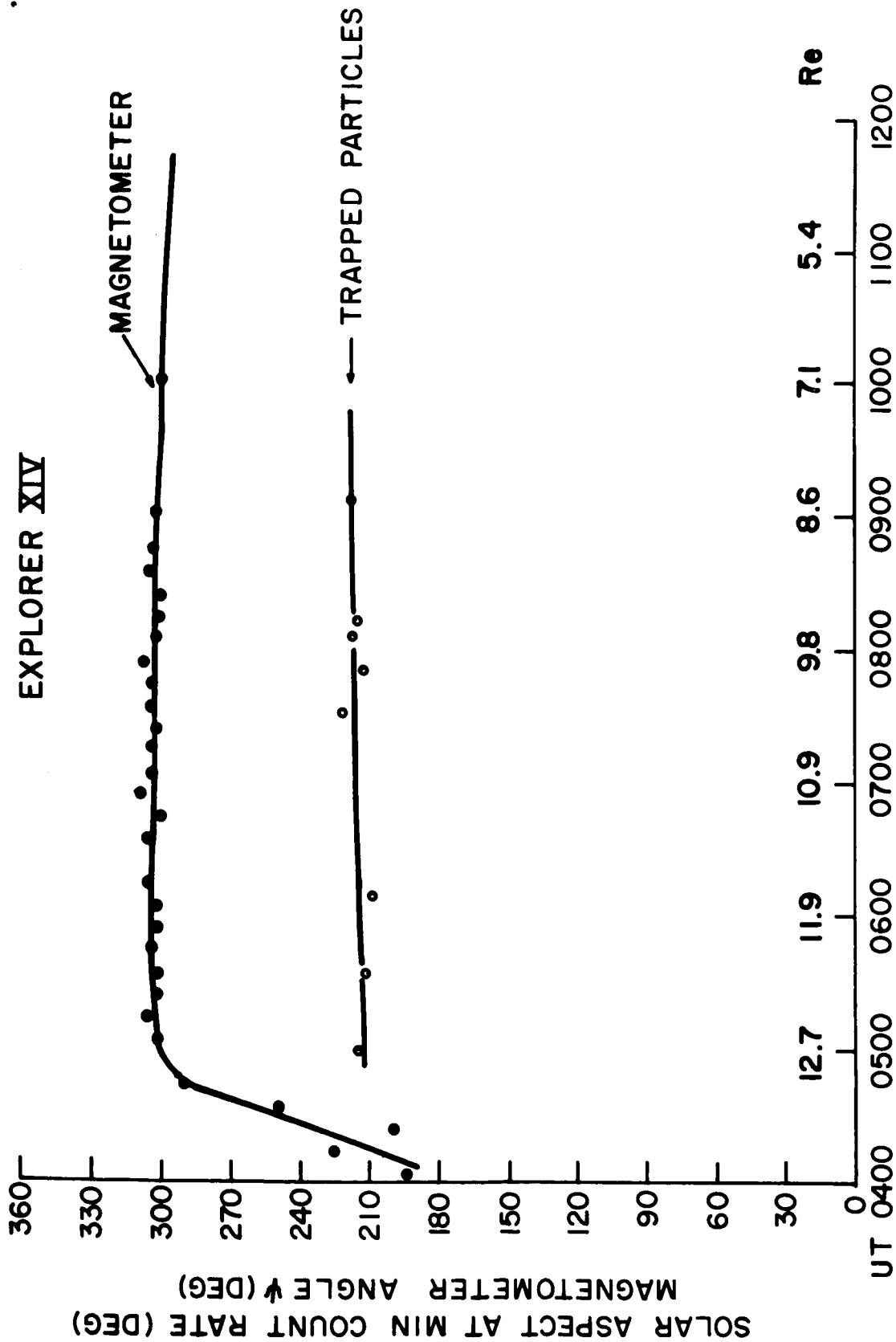
FIG. 27  
MAGNETIC FIELD INFORMATION



9 JANUARY 1963

**FIG. 28**

**INBOUND PASS OF JAN. 9, 1963**

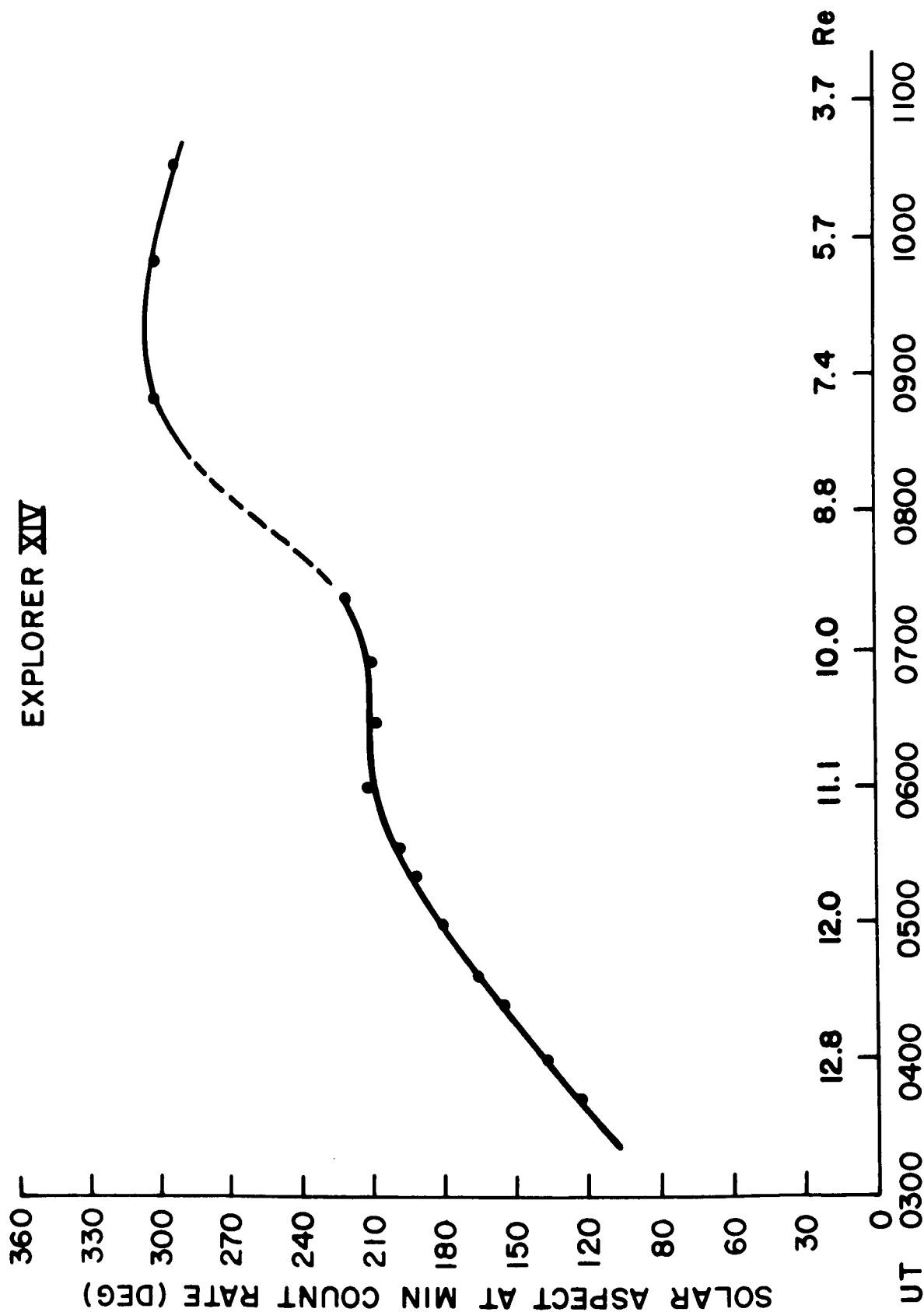


JAN. 9, 1963

FIG. 29

ANISOTROPIC FEATURES OF TRAPPED ELECTRONS  
COMPARED WITH LOCAL MAGNETIC FIELD MEASUREMENTS

# EXPLORER XIV



JAN. 6, 1963

FIG. 30

ANISOTROPIC FEATURES OF TRAPPED ELECTRONS

JAN. 6, 1963

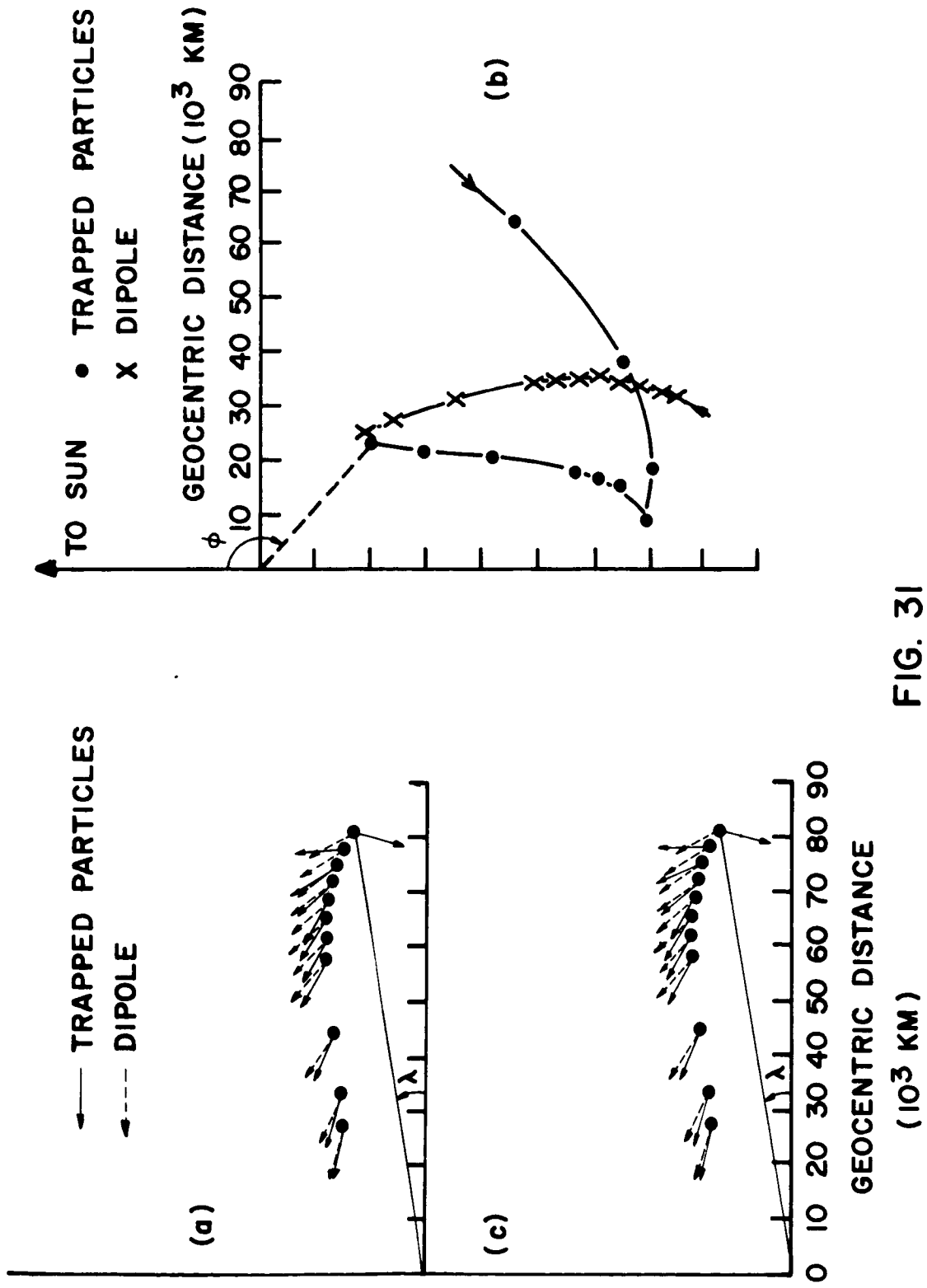


FIG. 31  
MAGNETIC FIELD INFORMATION

# EXPLORER XIV

JAN. 9, 1963

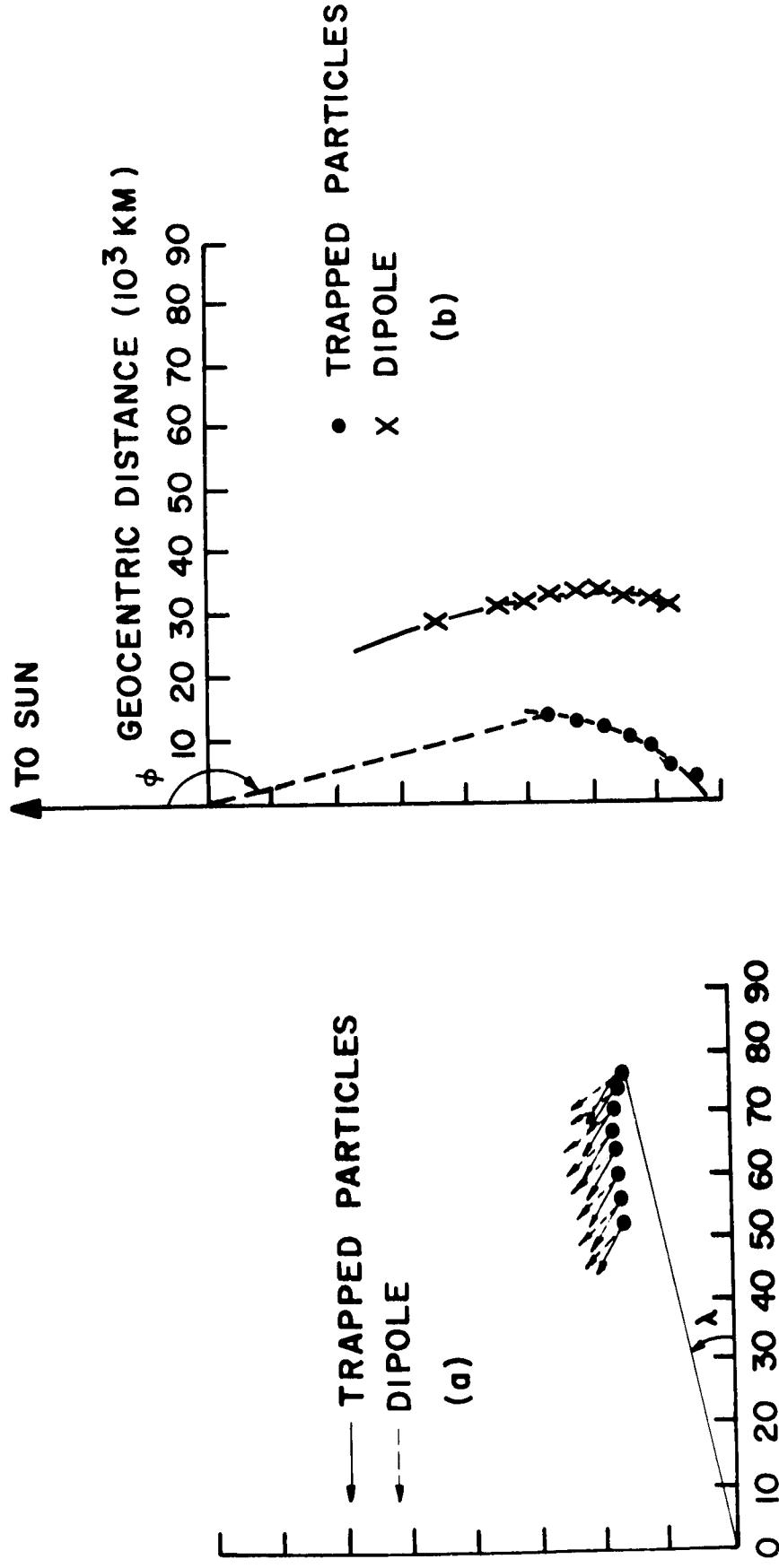


FIG. 32  
MAGNETIC FIELD INFORMATION

EXPLORER XIV

JAN. 9, 1963

○ — 0-180 DEG

● — 181-360 DEG

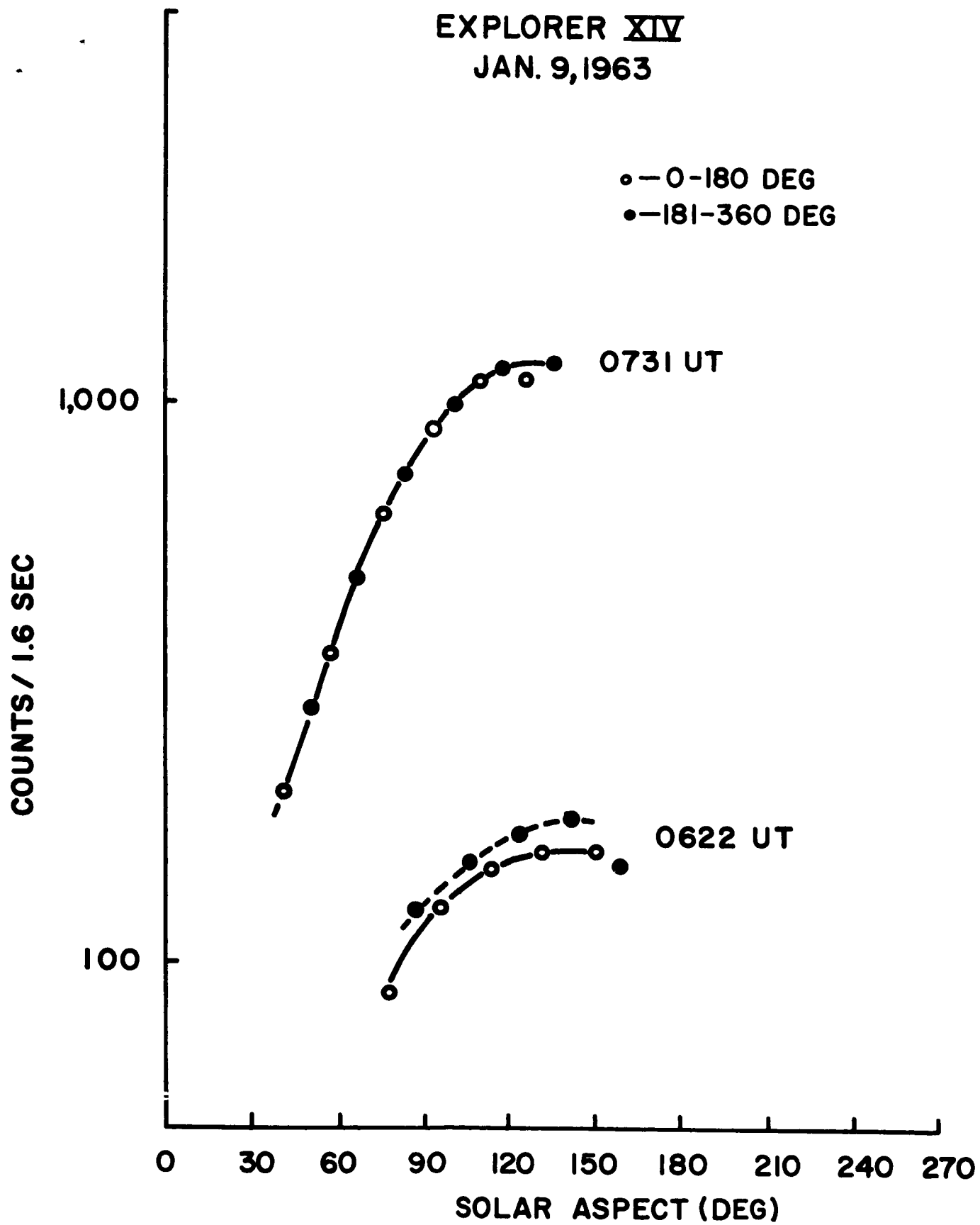


FIG. 33

STREAMING OF TRAPPED ELECTRONS

EXPLORER XIV--  
JAN. 24, 1963

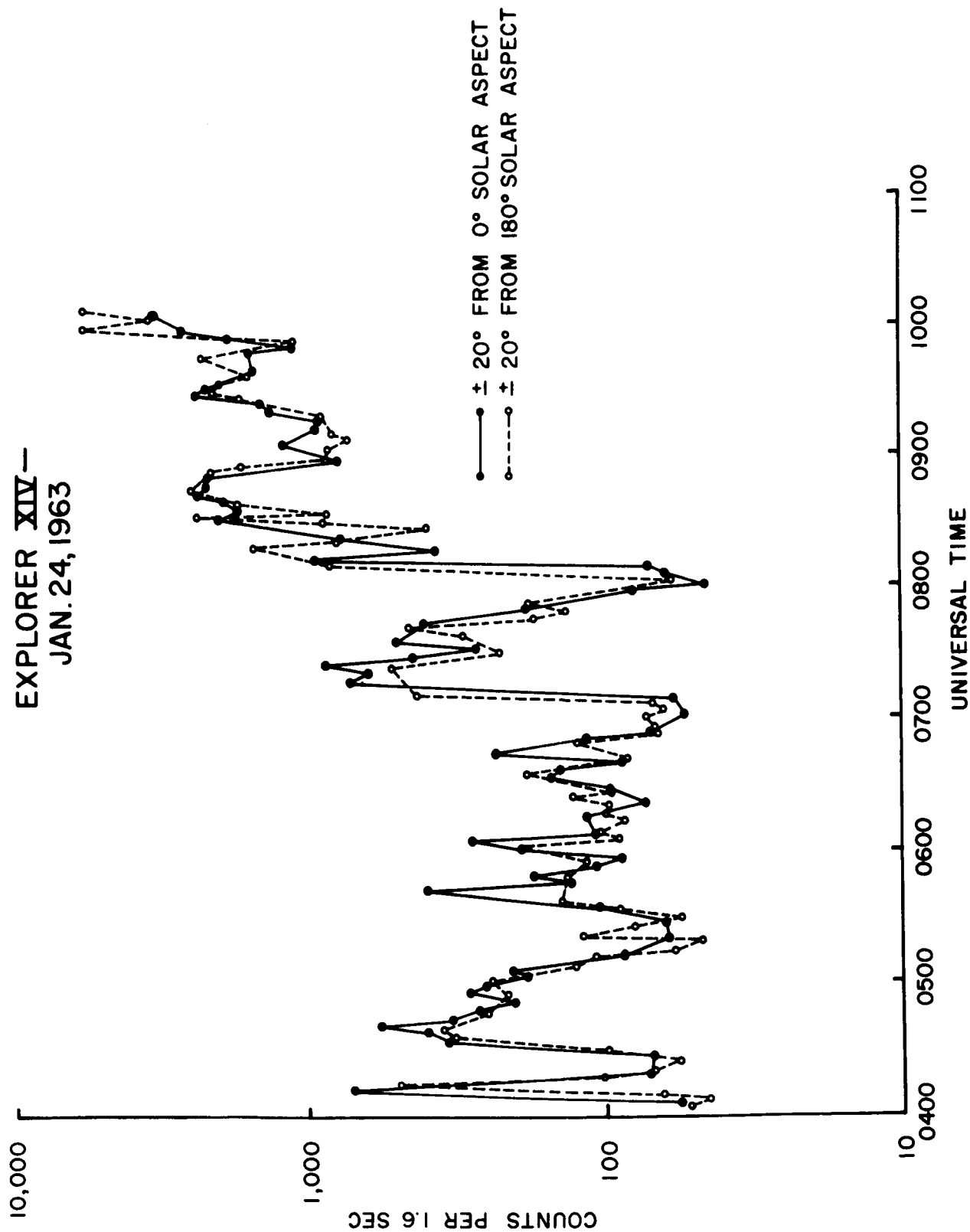


FIG. 34  
ANISOTROPIC FEATURES OF TAIL ELECTRONS

(a)

# EXPLORER XIV

(b)

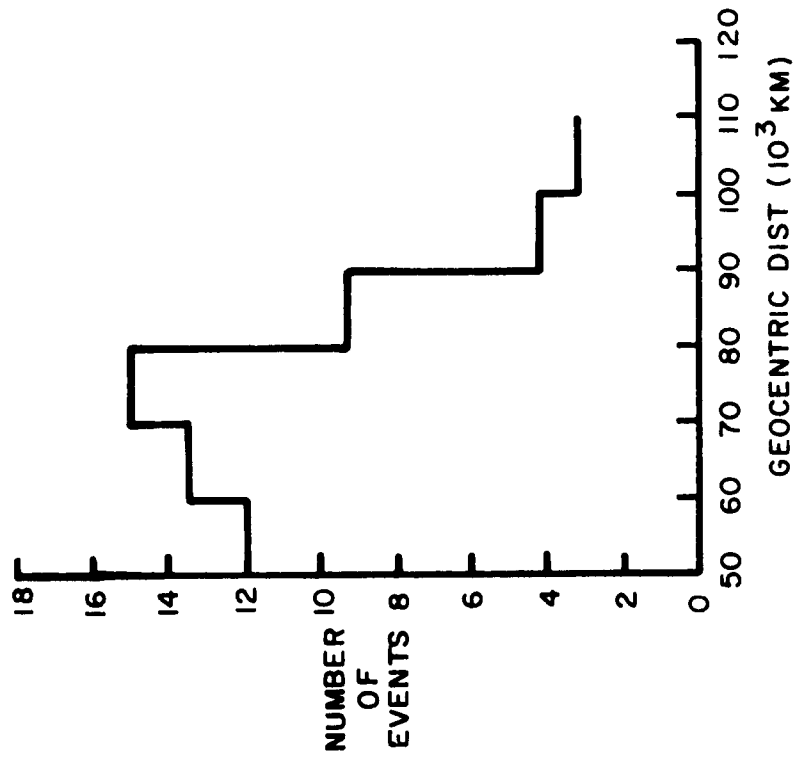
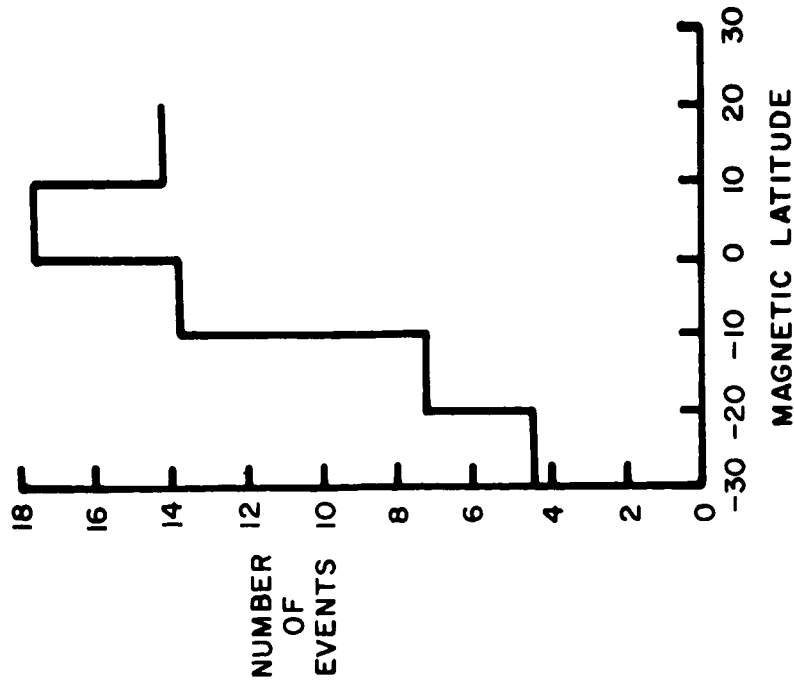
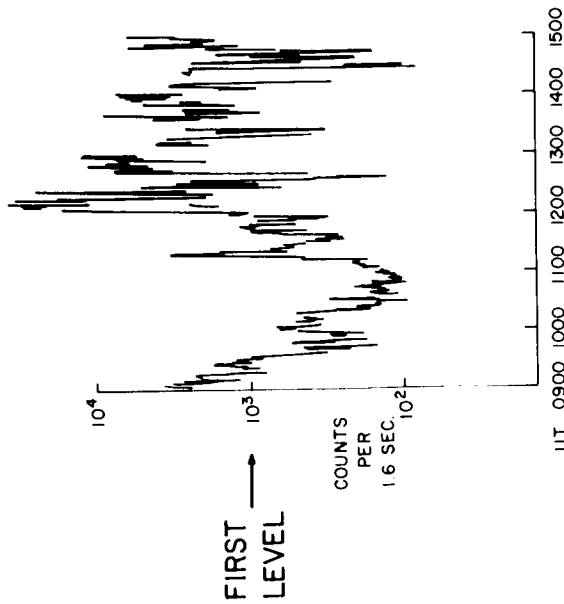


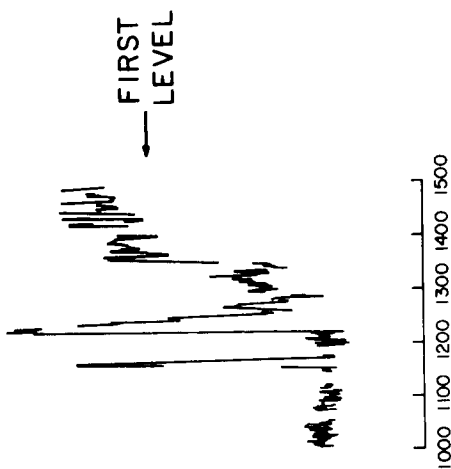
FIG. 35

ELECTRON "EVENTS" IN MAGNETOSPHERIC TAIL  
(a) DEPENDENCE ON MAGNETIC LATITUDE  
(b) DEPENDENCE ON GEOCENTRIC DISTANCE

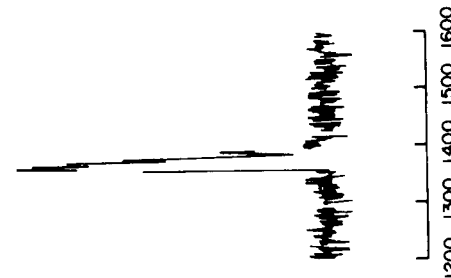
# BARROW



# COLLEGE



# COLLEGE



OCT. 24, 1962

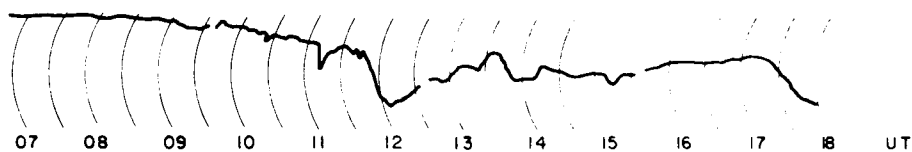
DEC. 25, 1962

FEB. 5, 1963

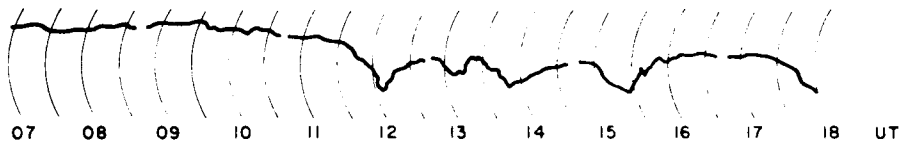
FIG. 36

CORRELATIONS BETWEEN MAGNETOSPHERIC  
ELECTRONS AND AURORAL ZONE MAGNETOGRAMS

Ft. YUKON

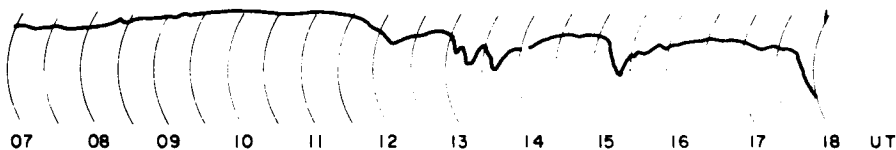


COLLEGE

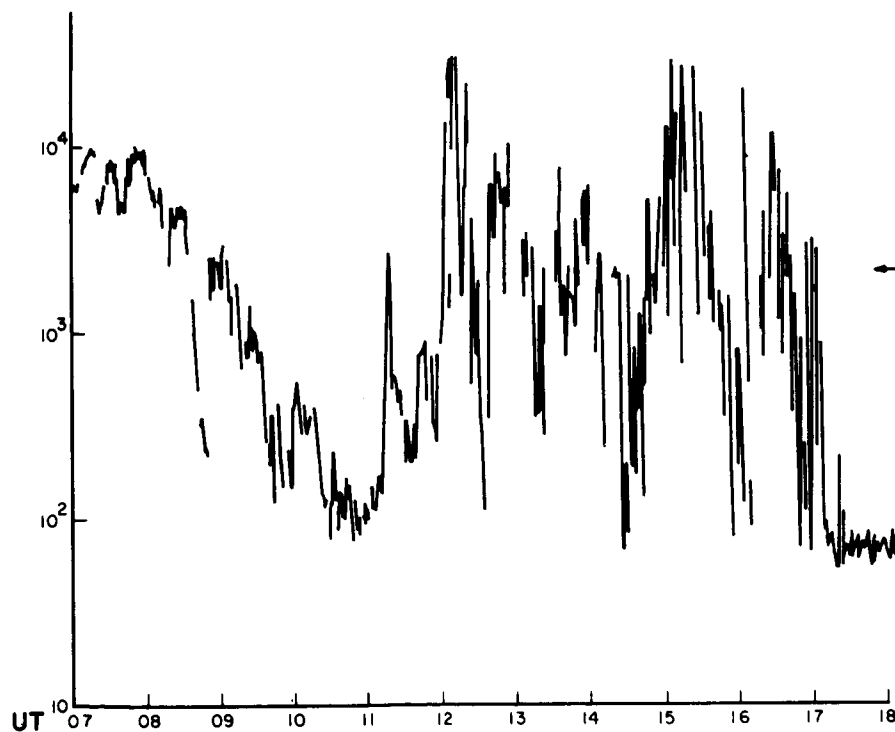


← RIOMETER RECORDS

HEALY



COUNTS PER  
1.6 SEC



← EXPLORER XIV  
FIRST LEVEL

OCT. 24, 1962

FIG. 37  
CORRELATION BETWEEN MAGNETOSPHERIC  
ELECTRONS AND RIOMETER RECORDS

## REFERENCES

- K. A. Anderson, H. K. Harris and R. J. Paoli, J. Geophys. Res., 70, 1039(1965).
- K. A. Anderson, Phys. Rev. Letters, 14, 888(1965).
- J. R. Asbridge, S. J. Bame, H. E. Felthausen, R. A. Olson and I. B. Strong, presented at the 46th Annual Meeting of the AGU, 1965.
- W. I. Axford and C. O. Hines, Can. J. Phys., 39, 1433(1961).
- W. I. Axford, J. Geophys. Res., 67, 3791(1962).
- W. I. Axford, H. E. Petschek and G. L. Siscoe, AVCO-Everett Research Report #190, August, 1964.
- D. B. Beard, J. Geophys. Res., 65, 3559(1960).
- L. Biermann, Observatory, 77, 109(1957).
- A. Bonetti, H. S. Bridge, A. J. Lazarus, B. Rossi and Scherb, J. Geophys. Res., 68, 4017(1963).
- H. S. Bridge, A. Egidi, A. Lazarus, E. Lyon and L. Jacobson, paper presented at the V COSPAR Symposium, Florence, Italy, 1964.
- H. Bridge, A. Egidi, E. Lyon, G. Moreno, S. Olbert and B. Rossi, presented at the 46th Annual Meeting of the AGU, 1965.
- W. L. Brown, W. N. Hess and J. A. Van Allen, J. Geophys. Res., 68, 605(1963).
- L. J. Cahill and P. G. Amazeen, J. Geophys. Res., 68, 1835(1963).
- L. J. Cahill, IGY Bulletin, 79, 231(1964).
- S. Chapman and V. C. A. Ferraro, Terrest. Magnet. Atm. Elec., 36, 77, 171(1931); 37, 147(1932); 38, 79(1933); 45, 245(1940).
- P. J. Coleman, L. Davis and C. P. Sonett, Phys. Rev. Letters, 5, 43(1960).
- J. W. Dungey, Cosmic Electrodynamics, Cambridge University Press, 1958.
- J. W. Dungey, Phys. Rev. Letters, 6, 47(1961).
- D. H. Fairfield, J. Geophys. Res., 69, 3919(1964).
- C. Y. Fan, G. Gloeckler and J. A. Simpson, Phys. Rev. Letters, 13, 149(1964).

- L. A. Frank, J. A. Van Allen, W. A. Whelpley and J. D. Craven,  
J. Geophys. Res., 68, 1573(1963).
- L. A. Frank, PhD thesis, Dept. of Physics and Astronomy, State  
University of Iowa, June, 1964.
- L. A. Frank and J. A. Van Allen, J. Geophys. Res., 69, 4923(1964).
- J. W. Freeman, PhD thesis, Dept. of Physics and Astronomy, State  
University of Iowa, June, 1963.
- J. W. Freeman, J. A. Van Allen and L. J. Cahill, J. Geophys. Res.,  
68, 2121(1963).
- T. Gold, J. Geophys. Res., 64, 1219(1959).
- K. I. Gringauz, V. G. Kurt, V. I. Moroz and I. S. Shklovskii, Astron.  
Zh., 37, 716(1960).
- J. P. Heppner, N. F. Ness, T. L. Skillman and C. S. Scarce,  
J. Geophys. Res., 68, 1(1963).
- J. R. Jokipii and L. Davis, Acceleration of Electrons Near the Earth's  
Bow Shock, preprint, 1964.
- F. S. Johnson, J. Geophys. Res., 65, 3049(1960).
- P. J. Kellogg, J. Geophys. Res., 67, 3805(1962).
- R. H. Levy, H. E. Petschek and G. L. Siscoe, AVCO-Everett Research  
Report #170, December, 1963.
- J. V. Lincoln, J. Geophys. Res., 68, 3302(1963).
- F. A. Lindemann, Phil. Mag., 38, 669(1919).
- I. B. McDiarmid and J. R. Burrows, J. Geophys. Res., 70, to appear,  
1965a.
- I. B. McDiarmid and J. R. Burrows, On an Electron Source for the Outer  
Van Allen Radiation Zone, preprint, 1965b.
- G. D. Mead and D. B. Beard, GSFC Document X-640-63-239, November, 1963.
- M. D. Montgomery, S. Singer, J. P. Conner and E. E. Stogsdill, Phys.  
Rev. Letters, 14, 209(1965).
- N. F. Ness, C. S. Scarce and J. B. Seek, J. Geophys. Res., 69,  
3531(1964).
- N. F. Ness, J. Geophys. Res., to appear, 1965.
- M. Neugebauer and C. W. Snyder, Science, 138, 1095(1962).

- B. J. O'Brien, J. Geophys. Res., 67, 3687(1962).
- B. J. O'Brien, J. Geophys. Res., 69, 13(1964).
- E. N. Parker, Phys. Fluids, 1, 171(1958).
- E. N. Parker, Interplanetary Dynamical Processes, Interscience Publishers, 1963.
- G. Pizzella, L. R. Davis and J. M. Williamson, GSFC Document X-611-64-384, December, 1964.
- F. L. Scarf, W. Bernstein and R. W. Fredricks, J. Geophys. Res., 70, 9(1965).
- C. W. Snyder and M. Neugebauer, Paper presented at the 4th COSPAR Symposium, Warsaw, Poland, 1963.
- C. W. Snyder, M. Neugebauer and U. R. Rao, J. Geophys. Res., 68, 6361(1963).
- J. A. Van Allen, G. H. Ludwig, E. C. Ray and C. E. McIlwain, Jet Propulsion, 28, 588(1958).
- J. A. Van Allen, L. A. Frank and B. J. O'Brien, J. Geophys. Res., 68, 619(1963).
- D. J. Williams and W. F. Palmer, J. Geophys. Res., 70, 557(1965).